National Aeronautics and Space Administration

NASA

Sensing Our Planet

NASA Earth Science Research Features *2015*

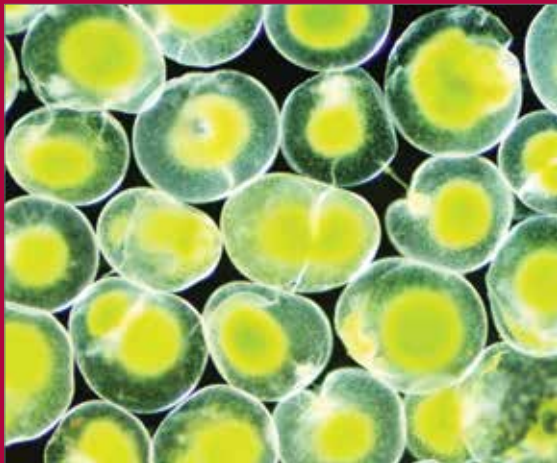# Sensing Our Planet

NASA Earth Science Research Features 2015

National Aeronautics and Space Administration

NASA Earth Observing System Data and Information System (EOSDIS)
Distributed Active Archive Centers

Front cover images

Top row, left to right:

This close-up of a dead tree shows depressions and pockets that are key areas to excavate cavities. Pileated woodpeckers, raccoons, and squirrels shelter within. The photo was taken in a subalpine burn on the upper slopes of Mount Harvey, British Columbia at an elevation of 1,600 meters (5,000 feet). See the related article, "Burned but not forgotten," on page 46. (Courtesy D. Brayshaw)

A mountain gorilla nestles within dense vegetation in the Mgahinga Gorilla National Park in Uganda. The park covers the northern slopes of three volcanoes in the Virunga Mountains, which are home to a large variety of wildlife, including about half the world's critically endangered mountain gorillas. See the related article, "Heart of drought," on page 28. (Courtesy W. White)

Ripe malbec grapes hang from the vine in Mendoza Province, Argentina. See the related article, "Stormy vineyards," on page 52. (Courtesy I. Lumb)

Mountain glaciers, such as Colony Glacier in Alaska, often terminate in a lake. See the related article, "A glacial pace," on page 6. (Courtesy E. Burgess)

Bottom row, left to right:

Noctiluca scintillans, a species of one-celled phytoplankton, are shown in this magnified image. Unlike most phytoplankton, *Noctiluca* are not capable of photosynthesis. They survive by trapping smaller phytoplankton with their whip-like flagellum and flushing them into their gullets. Otherwise, they grab free energy from millions of green phytoplankton living within their cell walls. See the related article, "Winter blooms in the Arabian Sea," on page 18. (Courtesy K. Al-Hashmi)

HMS *Edinburgh* endures storm force weather in the South Atlantic. Even with 8-meter (26-foot) waves crashing against the bridge, the ship managed to sustain no damage. See the related article, "Heavy weather, high seas," on page 24. (Courtesy D. Rosenbaum, Royal Navy Media Archive)

Locally grown fruits are sold at the San Francisco farmers market. See the related article, "Exposed orchards," on page 2. (Courtesy B. Doran)

Back cover images

Top row, left to right:

In this artist's rendition, an in-orbit explosion occurs when residual fuel within a rocket stage or satellite tank self-ignites. These discarded objects can deteriorate over time in the extreme temperatures and harsh environment of space. Leaks mixing with fuel components trigger such explosions, scattering debris in many directions and at varying speeds. See the related article, "Rubble trouble," on page 10. (Courtesy European Space Agency)
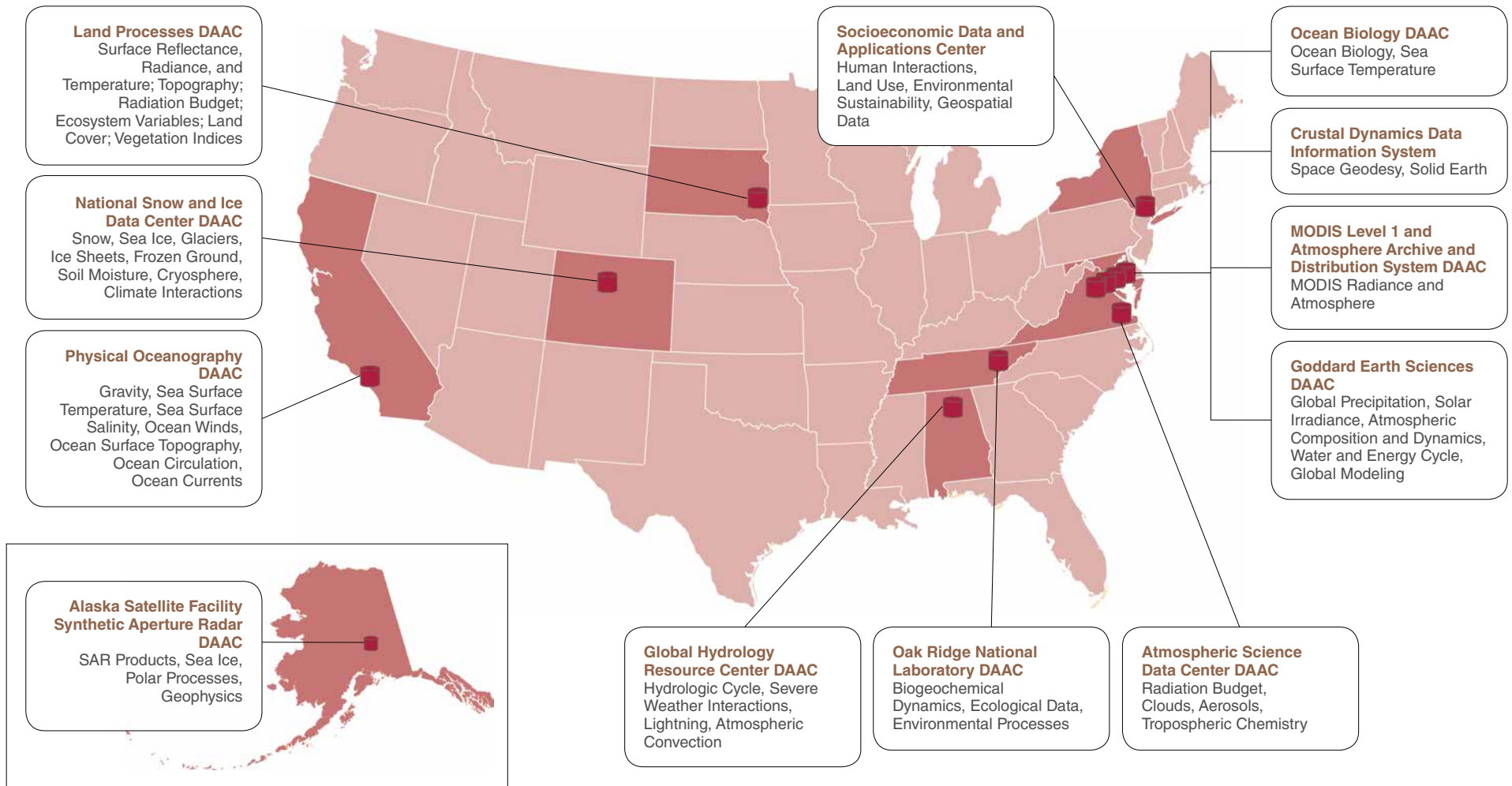
Canoes are moored at Playa de San Mateo del Mar on the Isthmus of Tehuantepec in Oaxaca, Mexico. See the related article, "Tracing the Tehuano," on page 38. (Courtesy L. Enriqueta)

Bottom row, left to right:

Researchers deploy an Argo float, a submersible instrument that records ocean temperatures and other data up to 2,000 meters (1.24 miles) deep. See the related article, "Missing heat," on page 34. (Courtesy Argo Program)

This view along Steensby Glacier in northern Greenland was seen during an Operation IceBridge survey flight on April 26, 2013. See the related article, "A submarine retreat," on page 42. (Courtesy NASA/M. Studinger)

Malayan tapirs are primarily nocturnal, so camera traps usually catch them at night. Their unique black-and-white coloring helps camouflage them in darkness. See the related article, "Trapping tapirs," on page 14. (Courtesy M. Linkie, Fauna & Flora International)

Land Processes DAAC
Surface Reflectance, Radiance, and Temperature; Topography; Radiation Budget; Ecosystem Variables; Land Cover; Vegetation Indices

National Snow and Ice Data Center DAAC
Snow, Sea Ice, Glaciers, Ice Sheets, Frozen Ground, Soil Moisture, Cryosphere, Climate Interactions

Physical Oceanography DAAC
Gravity, Sea Surface Temperature, Sea Surface Salinity, Ocean Winds, Ocean Surface Topography, Ocean Circulation, Ocean Currents

Alaska Satellite Facility Synthetic Aperture Radar DAAC
SAR Products, Sea Ice, Polar Processes, Geophysics

Socioeconomic Data and Applications Center
Human Interactions, Land Use, Environmental Sustainability, Geospatial Data

Ocean Biology DAAC
Ocean Biology, Sea Surface Temperature

Crustal Dynamics Data Information System
Space Geodesy, Solid Earth

MODIS Level 1 and Atmosphere Archive and Distribution System DAAC
MODIS Radiance and Atmosphere

Goddard Earth Sciences DAAC
Global Precipitation, Solar Irradiance, Atmospheric Composition and Dynamics, Water and Energy Cycle, Global Modeling

Global Hydrology Resource Center DAAC
Hydrologic Cycle, Severe Weather Interactions, Lightning, Atmospheric Convection

Oak Ridge National Laboratory DAAC
Biogeochemical Dynamics, Ecological Data, Environmental Processes

Atmospheric Science Data Center DAAC
Radiation Budget, Clouds, Aerosols, Tropospheric Chemistry

About the EOSDIS Distributed Active Archive Centers (DAACs)

The articles in this issue arose from research that used data archived and managed by NASA Earth Observing System Data and Information System (EOSDIS) Distributed Active Archive Centers (DAACs). The DAACs, managed by NASA's Earth Science Data and Information System Project (ESDIS), offer more than 8,200 Earth system science data products and associated services to a wide community of users. ESDIS develops and operates EOSDIS, a distributed system of discipline-specific DAACs and science investigator processing systems. EOSDIS processes, archives, and distributes data from Earth observing satellites, field campaigns, airborne sensors, and related Earth science programs. These data enable the study of Earth from space to advance scientific understanding.

For more information

"About the NASA Earth Observing System DAACs" (page 56)
NASA Earthdata Web site
   https://earthdata.nasa.gov
NASA Earth Science Web site
   http://science.nasa.gov/earth-science

About Sensing Our Planet

Each year, *Sensing Our Planet* features intriguing research that highlights how scientists are using Earth science data to learn about our planet. These articles are also a resource for learning about science and about the data, for discovering new and interdisciplinary uses of science data sets, and for locating data and education resources.

Articles and images from *Sensing Our Planet: NASA Earth Science Research Features 2015* are available online at the NASA Earthdata Web site (https://earthdata.nasa.gov/sensing-our-planet). Electronic versions of the full publication are available on the site. *Sensing Our Planet* is also available as an iBook from the Apple iBooks Store.

For additional print copies of this publication, please e-mail nsidc@nsidc.org.

Researchers working with EOSDIS data are invited to e-mail the editors at eosdis.editor@nsidc.org with ideas for future articles.

The design featured in this issue represents leaves. Several stories for 2015 spotlight how relatively small elements in an ecosystem, such as leaves, wood ash, phytoplankton, and water vapor, can have outsized effects on Earth's environment.

Printing notes

Printed with vegetable-based inks at a facility certified by the Forest Stewardship Council; uses 30 percent recycled chlorine-free paper that is manufactured in the U.S.A. with electricity offset by renewable energy certificates.

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Sensing Our Planet

NASA Earth Science Research Features 2015

Exposed orchards

by Natasha Vizcarra

Thick and sluggish, fog just about covers everything in California's Central Valley during the winter months. "As a kid, I thought the whole world was foggy in the winter," said biometeorologist Dennis Baldocchi. "Then in high school, my friends took me hiking along Mt. Diablo Range and, oh my God it was sunny! I got above the fog and it was a different world."

Now living in somewhat sunnier Berkeley, Baldocchi studies the connections between agriculture and climate. Several years ago he noticed that more farmers were asking him what was up with the fog. That included his father, who had been growing almonds and walnuts in the Central Valley for decades. "My dad was noticing a lot less fog than usual," Baldocchi said.

If fog is indeed dwindling, that is a huge concern to hundreds of farmers in one of the richest agricultural lands in the world. For decades, fog has protected certain crops from frying in the hot California sun. Less fog in the Central Valley would have implications for the entire country since California produces 95 percent of U.S. fruit and nut crops. Billions of dollars are also at stake, as the United States is the world's largest exporter of nuts.

Tule fog engulfs hills near Contra Costa, California. (Courtesy M. Crumpler)

Oatmeal-thick

California's Central Valley stretches out in a patchwork quilt of orchards, farms, and ranches. Only tractors and hulking sprinklers seem to move in the sun. This is the land that sends apricots, peaches, kiwis, almonds, walnuts, cherries, and pistachios to pantries in the United States and worldwide. The valley is bounded on the west by the Pacific Coast ranges and on the east by the Sierra Nevada Mountains, forming a slug-shaped trough 460 miles long and 60 miles wide.

It is in this trough that fog likes to settle for the winter. Fog is essentially a cloud sitting on the ground. It forms when water vapor close to the Earth's surface cools and condenses to form tiny water droplets. Fog tends to form in the early morning after a rainy day, then evaporates in the hot afternoon sun.

But the valley's oatmeal-thick and immovable tule fog, named after a freshwater marsh grass found all over the valley, has its own special recipe. In winter, cold and dense air sinks down the mountain ranges and into the valley, filling it to the brim. When this air is moist, such as after a storm, fog forms. Higher air pressure that lingers after a storm sits on the fog, keeping it from drifting away. And because the valley is an air basin, any pollution or fog that slips in is stuck there unless a strong storm lifts and pushes it out. So tule fog does not evaporate easily. It sticks around for days or weeks, a thick, white veil over the valley.

A shade for buds

Motorists hate it. Tule fog has caused many deadly pileups on Highway 99, which threads up through the center of the valley. Farmers, how-


Locally grown fruits are sold at the San Francisco farmers market. (Courtesy B. Doran)

ever, love it. Crops such as almonds, pistachios, cherries, apricots and peaches go through a necessary winter dormancy period when trees essentially go to sleep. They drop their leaves and slow their metabolism to shield themselves from the cold. Different trees need different amounts of chill hours, measured as air temperature below 7 degrees Celsius (45 degrees Fahrenheit). Pistachios, for example, need a minimum of 800 hours, while some grapes only need a few hundred.

Tule fog contributes to this chill. "It essentially provides shade for tree buds," said Katherine Pope, orchard systems advisor at the University of California Cooperative Extension. "A bud that's sitting out in the sun is going to be warmer than one that is shrouded in fog even if the air temperature is the same," Pope said. Without the fog, tree buds would be four or five degrees warmer than the air and may not achieve the

chill they need. Trees that get enough chill break their dormancy and regain their ability to blossom when spring arrives. A tree that does not get enough chill might bloom erratically, miss out on pollination, and fail to produce quality nuts or fruits.

Like Baldocchi, Pope had noticed a growing unease among valley farmers. "Everyone in the valley who has been paying attention has noticed a decrease in fog," she said. In Berkeley, Baldocchi verified his father's observation and checked fog records from airports. But these did not yield anything useful. "The records were extensive in time—which is great—but not representative of the whole region," he said. Next, he dug into satellite data, looking through images from the Moderate Resolution Imaging Spectroradiometer (MODIS) flying on the NASA Terra and Aqua satellites. But the MODIS data were not extensive enough. "With climate you really want to
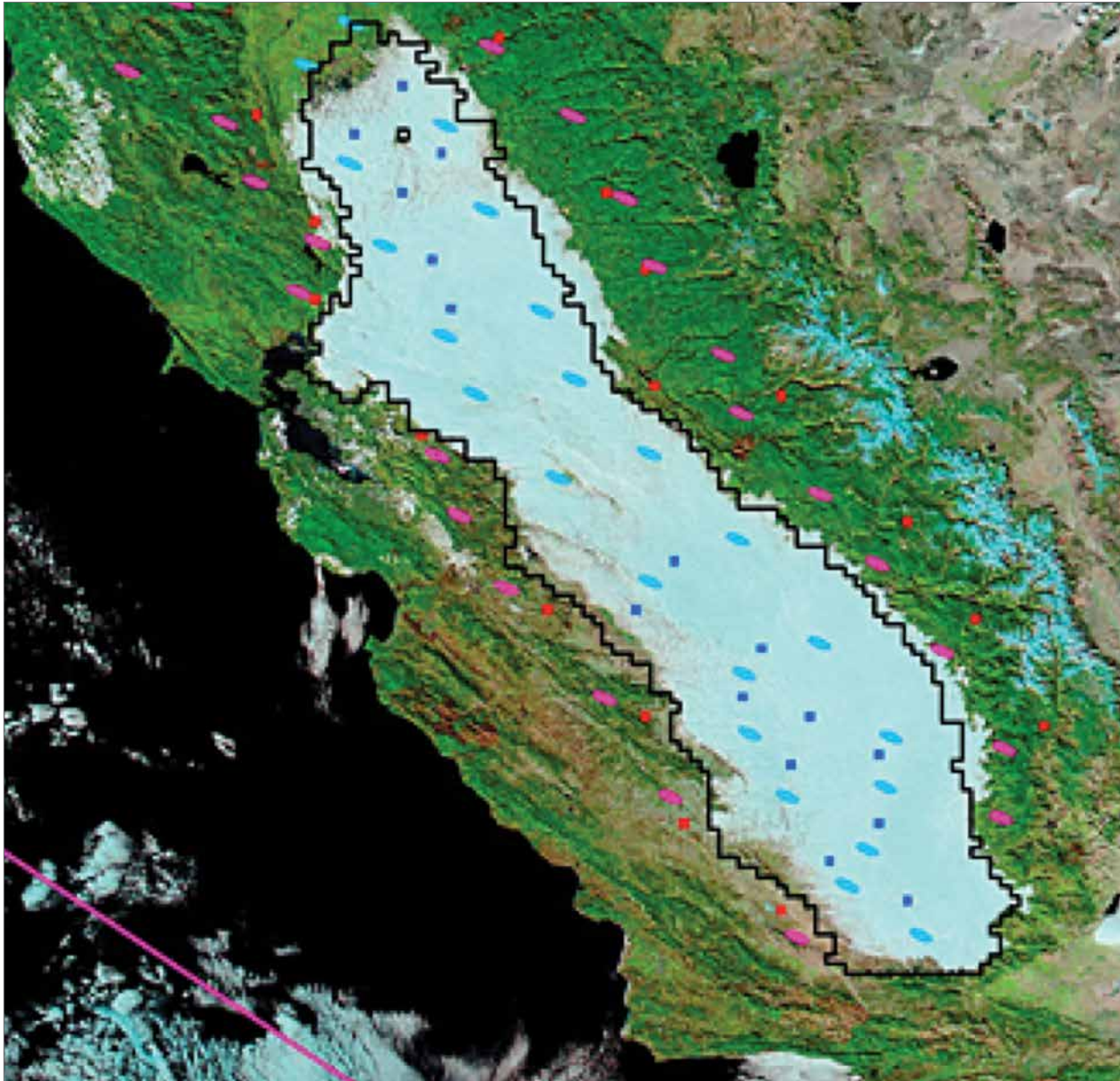
Tule fog fills the Central Valley of California on December 2, 2008. Blue squares and ellipses represent the pixels in the Central Valley that were evaluated in the Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) products, respectively. Red squares and pink ellipses represent pixels outside the valley that serve as reference points to the AVHRR and MODIS products. Together, the squares and ellipses are used to determine if the scene is representative of a tule fog day for AVHRR and MODIS. The black polygon outlines the average extent of typical fog episodes in the Central Valley, as detected by AVHRR. (Courtesy D. Baldocchi and E. Waller, 2014, *Geophysical Research Letters*)

have as long a record as possible," Baldocchi said. "MODIS only goes back to the year 2000."

Finding fog days

So Baldocchi worked with his student, Eric Waller, to stitch together surface reflectance data from MODIS and from the Advanced Very High Resolution Radiometer (AVHRR), a sensor on a fleet of satellites operated by the National Oceanic and Atmospheric Administration. The result was thirty-three years of data, long enough to see climate trends.

Piecing together a climate trend was not the only challenge. The researchers needed to separate cloud images from fog images. Baldocchi and Waller realized that because of the air basin effect, a satellite image of the valley on a tule fog day would show the slug-shaped trough of the valley itself. Clouds, on the other hand, would not be confined by the valley's shape and would hover over the Sierra Nevadas or the Pacific Coast ranges.

Waller worked on an algorithm to extract individual fog days from the thirty-three-year data set. The researchers also validated the satellite images with data from University of California weather stations. Fog varied from year to year, but on average, Baldocchi and Waller found a 46 percent drop in the number of winter fog days over the past thirty-two winters.

Follow the fog

The findings are bad news to valley farmers already reeling from a four-year drought. "During this drought, we had no fog at all," Baldocchi said. In a previous study, Baldocchi and his colleagues found that the annual winter chill hours are diminishing in the valley and have dropped

by several hundred since the 1950s. The researchers predicted that by the end of the 21st century, orchards in California are expected to receive less than 500 chill hours per winter. Other studies predict the climate in California to warm over the next 50 to 100 years.

While Baldocchi's findings may mean safer roads for the valley's commuters and more solar power for renewable energy enthusiasts, they could signal another huge transition in California's agricultural landscape. The last one came in the 1940s when rising water prices and shifting global markets forced California farmers to abandon cotton and wheat in favor of fruit and nuts. The decline in fog days and winter chill has yet to affect crop production and Pope says no study has tied these to decreases in yield. "But certainly, if this trend continues and we have increasing temperatures over winter, the two will exacerbate each other and will have yield consequences for California in the future," Pope said. And that ultimately means smaller harvests. "It's just going to be a matter of whether it will be in twenty years, or fifty years," Pope added.

Meanwhile in the valley, fruit breeders are already developing crop varieties that tolerate less winter chill. Proving new drought and heat tolerant strains, or moving orchards and bringing newly planted trees to production, can take years. "Farmers may also need to consider adjusting the location of orchards to follow the fog, so to speak," Baldocchi said. "Some regions along the foothills of the Sierra are candidates, for instance. That type of change is a slow and difficult process, so we need to start thinking about this now."

To access this article online, please visit https://earthdata.nasa .gov/sensing-our-planet/exposed-orchards.

About the remote sensing data

Satellites	Terra and Aqua
Sensor	Moderate Resolution Imaging Spectroradiometer (MODIS)
Data set	MODIS Surface Reflectance Daily L2G Global (MOD09GA, MYD09GA)
Resolution	1 kilometer and 500 meters
Parameter	Surface reflectance
DAAC	NASA Land Processes Distributed Active Archive Center (LP DAAC)

The researchers also used an AVHRR time series from the NASA Land Long Term Data Record.

About the scientists

Dennis Baldocchi is a biometeorologist and a professor at the Department of Environmental Science, Policy, and Management at the University of California Berkeley. His research interests include biometeorology and biosphere-atmosphere trace gas fluxes. The California Energy Commission supported his research. Read more at http://goo.gl/dIQvJv. (Photograph courtesy University of California Berkeley)

Katherine Pope is an orchard systems advisor at the University of California Cooperative Extension. Her research interests include phenology and tree crop research. The California Department of Food and Agriculture supported her research. Read more at http://goo.gl/BhYWEZ. (Photograph courtesy University of California)

References

Baldocchi, D., and E. Waller. 2014. Winter fog is decreasing in the fruit growing region of the Central Valley of California. *Geophysical Research Letters* 41, doi:10.1002/2014GL060018.

Baldocchi, D. D., and S. Wong. 2008. Accumulated winter chill is decreasing in the fruit growing regions of California. *Climatic Change* 87(S1): 153–166.

NASA Land Processes Distributed Active Archive Center (LP DAAC). MOD09GA and MYD09GA. USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD, 2015, doi:10.5067/MODIS/MOD09GA.006.

Pope, K. S., V. Dose, D. Da Silva, P. Brown, and T. M. DeJong. 2015. Nut crop yield records show bud-break based chilling requirements may not reflect yield decline chill thresholds. *International Journal of Biometeorology*, doi:10.1007/s00484-014-0881-x.

For more information

NASA Land Processes Distributed Active Archive Center (LP DAAC)
http://lpdaac.usgs.gov

NASA Moderate Resolution Imaging Spectroradiometer (MODIS)
http://modis.gsfc.nasa.gov

A glacial pace

"Measuring glacier velocities in this way allows us to estimate how much ice is calving off glaciers into the ocean."

Evan Burgess
University of Utah

by Laura Naranjo

In the low-lying Pacific island nation of Tuvalu, sea level rise is taking a toll. One of Tuvalu's uninhabited islands disappeared under the waves in 1997. And now, rising seas frequently flood the airport runway in the capital, Funafuti. New houses must be built on stilts. Tuvalu's prime minister, Enele Sopoaga, worries about the future. He wonders whether his country will survive, or whether it will disappear under the sea.

One third of sea level rise comes from thermal expansion, which occurs as warming ocean water expands slightly. The remaining rise comes from melting land ice. It is tempting to blame the vast Antarctic and Greenland ice sheets, as they contain 99 percent of all land ice on Earth. Yet they currently only contribute a third of sea level rise. The remaining third comes from mountain glaciers, such as those in Alaska, the Andes, and the Himalaya, which combined contain a mere 1 percent of land ice.

Evan Burgess, a researcher at the University of Utah, is trying to understand how such small glaciers can have such a big impact on sea level. Higher temperatures may seem obvious, but understanding glacier melt requires a more complex equation. Burgess said, "What matters is the

Mountain glaciers, such as Colony Glacier in Alaska, often terminate in a lake. (Courtesy E. Burgess)

glacier's net change in mass, and that's a combination of melt, snowfall, and calving. So you have to take into account all three." A glacier's status is measured by its mass balance: whether it is building mass through snowfall, losing mass through melt and iceberg calving, or remaining stable. By focusing on Alaska's glaciers, Burgess helped solve an important part of that equation.

Focus on Alaska

For most mountain glaciers, such as those in Alaska, small temperature changes can matter more, according to Alex Gardner, a researcher at the NASA Jet Propulsion Laboratory studying glaciers and sea level rise. "Imagine you're standing in the middle of the Antarctic continent at nearly ten thousand feet above sea level and hundreds of miles from the ocean, and average global temperatures go up by four degrees," Gardner said. "There will be no melt, because even the warmest month of the year is well below the melting point of ice. Whereas, with the 1 percent of ice that is located in more temperate areas, any change in atmospheric temperature during months with above freezing temperatures will manifest itself as an increase in melt."

Glaciers across Alaska have been retreating, and researchers have yet to discern what exactly is behind the melt. Complicating matters, most glaciers in Alaska terminate on land, while others—called tidewater glaciers—terminate in the ocean. "What we don't know is whether those glaciers are changing because of a change in the atmosphere," Gardner said. "Or are those glaciers responding to something that's going on in the ocean?" Rising air temperatures may cause region-wide retreat of glaciers, while warmer oceans can force tidewater glaciers to calve more ice and retreat. Untangling why Alaska's glaciers

are melting may help explain why glaciers around the globe are retreating.

Eyeing the offset

Measuring ice velocity helps scientists determine a tidewater glacier's mass balance. Satellites have tracked motion in the polar ice sheets, but remotely sensing smaller mountain glaciers proves trickier. "The challenge with studying places like Alaska or the Canadian Arctic or any of these smaller regions is that the glaciers are located in areas with complicated terrain. They're typically located in steep mountain ranges that can receive large amounts of precipitation and are frequently obscured by clouds," Gardner said. "So we have unique observational challenges that are not as much of a concern when analyzing measurements collected over the ice sheets."

Researchers also must tackle unique obstacles posed by regional climates. A variety of satellite instruments can monitor glacier speed, but few can see through cloudy, wet weather. Because Alaska gets a lot of rain, Burgess chose data from the Phased Array type L-Band Synthetic Aperture Radar (PALSAR) instrument on the Japan Aerospace Exploration Agency and Ministry of Economy, Trade and Industry (JAXA/METI) Advanced Land Observing Satellite (ALOS). The ALOS PALSAR data, although copyrighted by JAXA/METI, are made available through the Alaska Satellite Facility Synthetic Aperture Radar Distributed Active Archive Center (ASF SAR DAAC) to NASA scientists due to the strong partnership developed between JAXA and NASA. Burgess said, "L-Band radar, such as used by ALOS, is less sensitive to water, which allows us to track the glacier over a longer period of time. It makes the algorithm more robust to changes in weather." Tracking the glaciers with

Meltwater from mountain glaciers, such as Knik Glacier in Alaska, contribute a full third of sea level rise. Alaska's glaciers cover approximately 88,000 square kilometers (34,000 square miles). (Courtesy E. Burgess)

PALSAR data allowed Burgess to see persistent patterns in the glaciers.

To find ice velocity, Burgess selected two PALSAR images of each glacier taken on different dates, and compared them using offset tracking. "Offset tracking is basically just pattern matching," he said. "A computer algorithm searches for the same feature in two images acquired forty-six days apart." Although the satellite views the same spot on Earth repeatedly, it does not acquire images from exactly the same location, so Burgess corrected for the slight differences in the images. "We look at land areas that aren't moving and see how much shift there is from one image to the next and we correct, or pull that shift out, so that the two images are perfectly lined up," he said. Any remaining movement in the image pair reveals how fast the ice has moved.
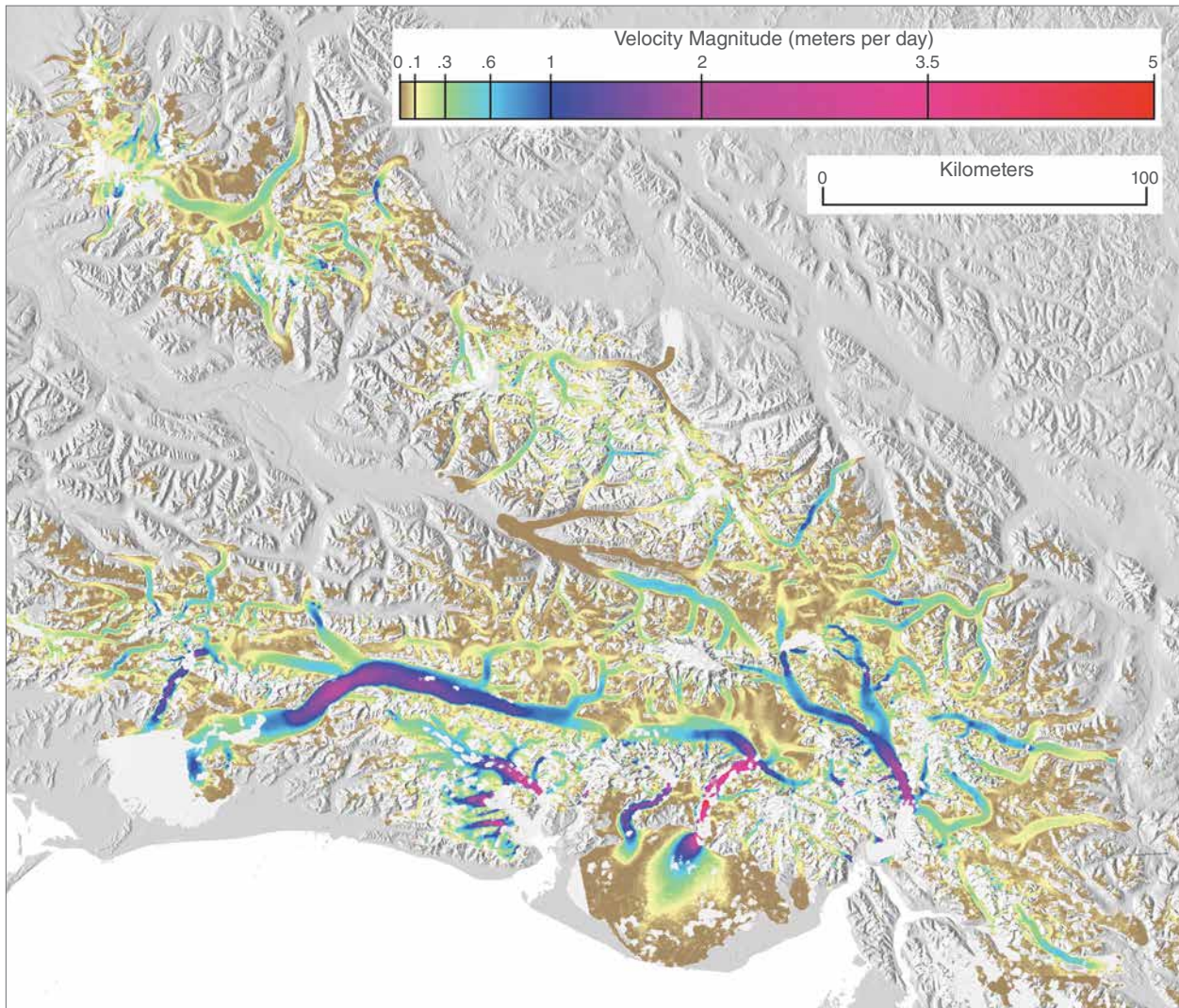
This data image shows wintertime flow speeds of glaciers in meters per day across the Wrangell and St. Elias Ranges. Light grey glacier outlines indicate missing data. Yellows and browns indicate low ice velocity; purples and reds indicate higher velocities. Data are from the Phased Array type L-Band Synthetic Aperture Radar (PALSAR) instrument aboard the Advanced Land Observing Satellite (ALOS). (Courtesy E. Burgess, includes material © JAXA, METI 2006-2011)

he's able to get a glimpse into whether this is a response to a change in ocean or a response to a change in atmosphere."

The value of velocity

Using these comparisons, Burgess created the first-ever maps of Alaskan glacier velocity, a baseline for future changes. And because he looked at wintertime glacier velocities, he made an unexpected find about glacial motion: summer melt influenced winter flow speeds. During summer, melt water drains through glacier ice, lubricating the glacier bed. But over the summer, this same water bores tunnels in the ice, allowing the water to drain from the glacier in the fall. "We found that in summers with more melt, better channel development helps glaciers drain better and reduces flow speed of glaciers throughout Alaska come winter. This upends a widespread understanding throughout the community that glacier velocities in winter don't really change," Burgess said. His research also suggests that unusual increases in summertime glacier velocity from summer melt are largely countered by slower ice velocity the following winter.

This finding is critical to understanding glacial processes, especially in relation to sea level rise. Under normal conditions, these alternating speeds can be a glacial self-regulating mechanism that helps maintain mass balance. Gardner said, "If you do get that temporary speed-up, it's countered by a slow-down in winter. And it tells us that these systems are more stable than we initially thought."

Conditions for many mountain glaciers are no longer consistently normal, however, and one of the keys to understanding short-term sea level rise is knowing how mountain glaciers are

Tracking mass balance can reveal that glaciers are changing, but looking at velocity can help reveal why. "Measuring glacier velocities in this way allows us to estimate how much ice is calving off glaciers into the ocean," Burgess said. If tidewater glaciers accelerate, that may signal ocean warming. If flow speeds of all mountain glaciers change, that signals other effects from atmospheric changes. Gardner said, "What Evan's done is quantified all glacier velocities for Alaska, so

changing. The ice velocity maps Burgess created are now available from the ASF SAR DAAC, and help fill a gap in the mass balance equation for Alaska's glaciers as they continue to change. Burgess said, "Most of the tidewater glaciers have pulled up almost to the point of getting out of the water. And this changes how those glaciers interact with climate, so we're expecting a lot of changes in their flow dynamics."

Even after tidewater glaciers become land-terminating glaciers, their melt water ends up in rivers that eventually run off into the ocean. Keeping an eye on ice velocity and mass balance will help researchers project sea level rise and gain more insight about the climate forces acting on glaciers. Sea level rise remains complicated, a tangle of processes gradually reshaping the world's coastlines. "When it comes to century-scale sea level change, which is important to us as a society and to the engineering of coastal communities, these regions are very important," Gardner said.

To access this article online, please visit https://earthdata.nasa .gov/sensing-our-planet/a-glacial-pace.

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References

Burgess, E. W., R. R. Forster, and C. F. Larsen. 2013. Flow velocities of Alaskan glaciers. *Nature*, doi:10.1038/ncomms3146.

Burgess, E. W., C. F. Larsen, and R. R. Forster. 2013. Summer melt regulates winter glacier flow speeds throughout Alaska. *Geophysical Research Letters* 40: 6,160–6,164, doi:10.1002/2013GLO58228.

Gardner, A. S., G. Hoholdt, J. G. Cogley, B. Wouters, A. A. Arendt, et al. 2013. A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science* 340, doi:10.1126/science.1234532.

NASA Alaska Satellite Facility Synthetic Aperture Radar Distributed Active Archive Center (ASF SAR DAAC). 2012. ALOS PALSAR data. Copyrighted by JAXA,

METI. Fairbanks, AK, USA: NASA ASF DAAC. https://www.asf.alaska.edu/sar-data/palsar/about-palsar.

NASA Land Processes Distributed Active Archive Center (LP DAAC). 2012. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Map (GDEM). USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD. https://lpdaac.usgs.gov/dataset_ discovery/aster/aster_products_table/astgtm.

Warne, K. 2015. Will Pacific island nations disappear as seas rise? Maybe not. *National Geographic*, http://news .nationalgeographic.com/2015/02/150213-tuvalu -sopoaga-kench-kiribati-maldives-cyclone-marshall -islands.

About the remote sensing data

Satellites	Japan Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS)	Terra
Sensors	Phased Array type L-Band Synthetic Aperture Radar (PALSAR)	Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)
Data sets	ALOS PALSAR L1.0	ASTER Global Digital Elevation Model (ASTGM)
Resolution	Nominal 9 meter ground resolution	30 meters
Parameters	Terrain	Elevation
DAACs	NASA Alaska Satellite Facility Synthetic Aperture Radar Distributed Active Archive Center (ASF SAR DAAC)	NASA Land Processes DAAC (LP DAAC)

About the scientists

Evan Burgess is a research assistant professor in the Department of Geography at the University of Utah. He studies glacier mass balance and dynamics, glacier response to climate, surging glacier dynamics, and synthetic aperture radar remote sensing and offset tracking. The NASA Earth Science Space Fellowship supported his research. Read more at http://goo.gl/ZaS9wg. (Photograph courtesy E. Burgess)

Alex Gardner is a research scientist in the Earth Sciences Division of the Jet Propulsion Laboratory. He studies Earth's cryosphere, focusing on glaciers and their impacts on sea level rise and water sources, and how glaciers respond to natural and human induced forcing. The Natural Sciences and Engineering Research Council of Canada supported his research. Read more at https://goo.gl/UL2uOw. (Photograph courtesy A. Gardner)

For more information

NASA Alaska Satellite Facility Synthetic Aperture Radar Distributed Active Archive Center (ASF SAR DAAC) https://www.asf.alaska.edu

NASA Land Processes DAAC https://lpdaac.usgs.gov

Advanced Land Observing Satellite (ALOS) Phased Array type L-Band Synthetic Aperture Radar (PALSAR) https://www.asf.alaska.edu/sar-data/palsar

Burgess, et al. data set: Alaska Glacier Flow Speed, 2007-2011 https://www.asf.alaska.edu/other-data/glacier-speed

Rubble trouble

"The intention is not to catalog space debris, but to refine predictions."

Harald Wirnsberger
Austrian Academy of Sciences

by Agnieszka Gautier

Checking the weather, sending a text, or updating Facebook requires bouncing a signal between Earth and satellites. The remains of these communication satellites, along with sixty years of space activity, have littered outer space. An orchestra of objects swirls in various orbits: decommissioned satellites, burnt-out rocket stages, lost tools, and fragmented particles from explosions and collisions. When tiny flecks of paint travel with enough force to cut cables, damage space shuttle windows, or kill astronauts, accurately tracking debris matters.

About 500 miles above Earth's atmosphere spins the defunct European Space Agency Environmental Satellite (Envisat). Weighing eight tons and large as a Greyhound bus, it is at high risk for collision. The Space Surveillance Network (SSN) operated by the U.S. Air Force routinely tracks debris in space, but Harald Wirnsberger and a

In this artist's rendition, an in-orbit explosion occurs when residual fuel within a rocket stage or satellite tank self-ignites. These discarded objects can deteriorate over time in the extreme temperatures and harsh environment of space. Leaks mixing with fuel components trigger such explosions, scattering debris in many directions and at varying speeds. (Courtesy European Space Agency)

team of researchers from the Austrian Academy of Sciences want to offer an alternative to monitoring space debris that is available to any nation. Their recent study, using multiple lasers to track Envisat, offers public alternatives to what is now mainly military-controlled information.

Soundless booms

More than 20,000 pieces of debris, softball sized and larger, orbit the Earth. About half a million pieces are marble sized. But millions of pieces are too small to track. "All these pieces are moving with high velocity in the range of 8 kilometers per second," said Georg Kirchner, a member of Wirnsberger's team. That is equivalent to 17,500 miles per hour, or ten times faster than a bullet.

"All these objects are in different orbits, mainly where they were launched," Kirchner said. When objects in different orbits intersect, their collision, crashing at thousands of miles per hour, may lead to a domino effect referred to as the Kessler syndrome. Each collision increases the likelihood of future collisions. A 30 percent rise in space debris resulted from a Chinese anti-satellite test in 2007, and from the accidental collision of a defunct Russian satellite with a functioning U.S. commercial satellite in 2009. The two collisions added more than 5,000 pieces of traceable debris.

Most debris cycles in low Earth orbit, between 100 to 1,250 miles above the planet. The SSN detects, tracks, and catalogs objects orbiting Earth. They predict when and where objects de-orbit, or re-enter the Earth's atmosphere. They also distinguish between objects and missiles because radar by itself cannot. And they inform NASA of potential collisions with satellites or the International Space Station (ISS). From 1998 to 2012, the ISS performed fifteen evasive maneuvers. When space debris is identified too late for a maneuver, the station crew must evacuate, which has occurred three times since 2009.

Currently, the SSN uses optical telescopes and ground-based radars that send microwaves into space. These methods, however, have an accuracy ranging from several hundreds of meters to a few kilometers. Satellite Laser Ranging (SLR) has proven to be an alternative to improve debris surveillance in the low Earth orbit, shrinking accuracy to a few meters and even tenths of meters.

A ground network of fifty-two SLR stations around the world shoots short pulses of light at satellite reflectors to measure the time of round-trip flight. This provides instantaneous range measurements, precisely tracking satellite locations within millimeters. SLR has also supported research in geodesy, geophysics, lunar science, and fundamental constants. "Tracking debris without reflectors is a new field for laser ranging," Wirnsberger said. "The intention is not to catalog space debris, but to refine predictions." But arbitrarily pointing a laser into space is not efficient. First of all, if photons come back, it is not clear what they hit. To initially track a debris target, the team used orbital information provided by a coordination system called Two-Line Elements (TLE), created by the United States Air Force. Over 70,000 objects have been cataloged.

Cat eyes

"We had a target up there," Kirchner added. Envisat was launched in 2002, carrying nine instruments to gather observations of Earth. It was meant to last five years, but outlived its projection by another five.

A Satellite Laser Ranging (SLR) Station at Graz Observatory in Austria beams a laser into space, tracking the Environmental Satellite (Envisat). This SLR station acts as the active station, sending off photons, while nearby stations act as passive stations, receiving the Graz photons. (Courtesy H. Wirnsberger)

"The advantage of Two-Line Elements is that they are simple to use and available for most targets," Kirchner said. They are accessible from the Internet. It allows researchers to pre-calculate where to expect an object. "But these publicly available predictions have an uncertainty in the range of kilometers," Wirnsberger said.

Two classes of objects orbit Earth: cooperative and uncooperative. Cooperative objects are equipped with retroreflectors, attached to satellites with the intention of being tracked. "Retroreflectors are similar to what we call cat eyes in German," Kirchner said, "those things on the side of the street, reflecting light back in the same

This illustration shows where diffuse photons were picked up by three other passive stations: Zimmerwald, Switzerland; Herstmonceux, England; and Wettzell, Germany. The Satellite Laser Ranging station at Graz, Austria, sent out the initial pulse, rendering it the active station. (Courtesy P. Ruzek, Astronomy Institute University Bern, Switzerland)

of SLR stations, the team increased the number of stations receiving photons, calling them passive stations.

Knowing where to shoot, the active Graz station pointed up. Nearby stations in England, Switzerland, and Germany acted as passive stations, waiting for the return travel of the Graz photons. Time bias could throw everything off, however. So synchronization between participating stations was key.

Then, the researchers compared firing only the Graz laser and processing the single station round trip time of flight, and firing Graz but also incorporating multiple passive stations. "So with one shot we had two or more measurements," Kirchner said. More measurements from different locations provided better orbit prediction. Using one passive station improved orbit predictions by a factor of ten. "Simple geometry helps with accuracy," Kirchner said.

Laser ranging activities are organized under the International Laser Ranging Service (ILRS), which provides global satellite and lunar laser ranging data. The teams' derived data are archived at the Crustal Dynamics Data Information System, a NASA Distributed Active Archive Center and one of two data centers that support ILRS.

To move or not to move

Laser ranging works for debris at least 1 square meter (11 square feet) and no higher than 3,000 kilometers (1,900 miles) above Earth. So the most polluted orbits are within reach. "It is quite impressive to send photons out where there are no reflectors, only diffuse reflection, and detect it at a distant passive station. These data can

direction where light was coming." Objects from collisions or lost items released by astronauts have no reflectors. They are uncooperative objects. To date, these have been the most difficult to track.

Envisat is equipped with retroreflectors, but the satellite has started spinning since it lost contact with Earth. It behaves like an uncooperative target. "An active satellite can correct its spin, but if it is no longer active then it often starts oscillating," Kirchner said. Collisions will oscillate satellites. So will explosions. When fuel tanks deteriorate in the extreme temperatures of

space, the residual fuel within may ignite and increase torque.

Most SLR stations are incapable of tracking objects without reflectors. When a laser beam hits an uncooperative object, photons reflect diffusely. Rather than a round trip shot, the photons spread out against the surface of the target, like marbles bouncing off of a toy school bus. Some of the photons will make their way back to give an estimate of distance based on time traveled. "But only three stations demonstrated this is possible," Wirnsberger said. To extend the sparse network

be used to provide orbit predictions in a short period of time," Wirnsberger said. "The concept is new and great."

The better the accuracy of orbit prediction, the better the decisions of how to function in space. Evasive maneuvers take energy. "Fuel is a main limitation for satellite lifespan," Kirchner said. So if a satellite is predicted to come within 300 meters, give or take 500 meters, of a discarded rocket stage in five days, there is no certainty in the prediction. But with improved accuracy—a give or take of 100 meters—satellite operators may have confidence to avoid a maneuver.

With the growth in clutter, space exploration will be more costly and dangerous. Future generations will need to penetrate a layer of debris with more accuracy, planning for more fuel for evasive maneuvers and for more shields critical against small debris. Low Earth orbit may even become impassable.

Given Envisat's orbit and size, it will take about 150 years to gradually fall into Earth's atmosphere. So it is a good candidate for removal from orbit. But how feasible is that? "The most progressive answer," Kirchner said, "would be not yet. And the most hesitating answer would be never." Spin is a big part of the challenge. To remove a satellite, something needs to be sent to attach to the target, and then together they would need to return. "You have to know how fast satellites are spinning if you want to remove them," Wirnsberger said. The team is working on refining predictions to determine spin rate. Satellite Laser Ranging is proving to have more capabilities than initially anticipated. And with time, through cooperative knowledge, debris clean up may become more of a reality.

About the remote sensing data

Sensor	Satellite Laser Ranging stations
Data set	Satellite Orbit Predictions
Spatial extent	Bounding Rectangle: (90.0°, -180.0°, -90.0°, 180.0°)
Temporal resolution	1 day
Parameter	Orbit predictions
DAAC	NASA Crustal Dynamics Data Information System (CDDIS)

About the scientists

Georg Kirchner heads the Satellite Laser Ranging group within the Space Research Institute of the Austrian Academy of Sciences. His research interests include everything related to Single Laser Ranging such as hardware, software, and single-photon detectors. The Austrian government and the European Space Agency supported his research. (Photograph courtesy W. Hausleitner)

Harald Wirnsberger is a research associate at the Space Research Institute of the Austrian Academy of Sciences. His research interests include satellite geodesy, celestial mechanics, dynamic modeling, and parameter estimation, with a special focus on space debris orbit determination and orbit prediction. The Austrian Research Promotion Agency within the Austrian Space Applications Program supported his research. (Photograph courtesy H. Wirnsberger)

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Wirnsberger, H., O. Bauer, and G. Kirchner. 2015. Space debris orbit prediction errors using bi-static laser observations. Case study: ENVISAT. *Advances in Space Research* 55: 2,607–2,615, doi:10.1016/j.asr.2015.02.018.

References

Kirchner, G., F. Koidl, F. Friederich, I. Buske, U. Völker, and W. Riede. 2013. Laser measurements to space debris from Graz SLR station. *Advances in Space Research* 51: 21–24, doi:10.1016/j.asr.2012.08.009.
NASA Crustal Dynamics Data Information System (CDDIS). Satellite Orbit Predictions. Greenbelt, MD, USA. http://cddis.gsfc.nasa.gov/Data_and_ Derived_Products/SLR/Orbit_predictions.html.

For more information

NASA Crustal Dynamics Data Information System (CDDIS)
http://cddis.gsfc.nasa.gov
International Laser Ranging Service (ILRS)
http://ilrs.gsfc.nasa.gov
Orbital debris information
http://www.nasa.gov/mission_pages/station/news/ orbital_debris.html
http://www.esa.int/Our_Activities/Operations/ Space_Debris

Trapping tapirs

"The Malayan tapir needs champions."

Matthew Linkie
Fauna & Flora International

by Laura Naranjo

Tiger conservationist Matthew Linkie recalls the first and only time he's seen a wild Malayan tapir. He and his field crew were packing up camp one morning when a guide started shouting. "There was this huge tapir, maybe twenty or thirty meters in front of us," Linkie said. "You're in this rainforest and the sun's coming up and all these brilliant greens are coming through the forest. Then there's this big black and white blob the size of a small car crossing the river. Absolutely incredible." Linkie's daylight sighting was rare: Malayan tapirs are reclusive, nocturnal creatures that prefer traversing the thick rainforest understory in darkness.

Malayan tapirs are primarily nocturnal, so camera traps usually catch them at night. Their unique black-and-white coloring helps camouflage them in darkness. (Courtesy M. Linkie, Fauna & Flora International)

Their nocturnal roaming helps promote plant diversity because tapirs spread seeds as they eat, perpetuating a cycle that helps distribute plants and regenerate forests. But Malayan tapirs are endangered. And they have been very difficult for conservationists to monitor—that is, until Linkie noticed tapirs showing up in camera trap data. Motion-triggered cameras, strung throughout the rainforests of Southeast Asia, are designed to capture snapshots of any warm-bodied animal moving through the forest. Because tapirs shy away from human contact, Linkie wondered if these traps could help monitor them. Likewise, could he learn whether human activities disturb the tapir's already dwindling habitat?

Of tigers, traps, and tapirs

Related to the horse and rhinoceros, tapirs look like neither. Instead, they are somewhat pig-shaped and sport a long, flexible snout. "It's a funny-looking animal but it's a beautiful animal, as well," said Linkie. Of the four tapir species, Malayan tapirs are the largest. What really sets them apart is their bold, panda-like coloring: black head and legs contrasted by a moon-white body and rump.

Initially, Linkie used camera traps to study tigers, since traps have proven efficient in thick jungle foliage. "The rainforest is really, really dense, so when you go walking through you can't really deviate off the main trails," Linkie said. "So a lot of these rainforest mammals, the large-bodied ones, tend to stick to the same trails." Installing camera traps along these established trails enables researchers to remotely monitor a variety of species in ways that were not previously possible.

While scanning for tigers in trap photographs, Linkie realized traps could also track the some-

what neglected Malayan tapir. "In Latin America, tapirs are one of the best studied mammal species," he said. In Asia, however, tapirs tend to be disregarded in favor of more charismatic animals such as rhinoceroses or elephants. "The Malayan tapir needs champions," Linkie said.

In spite of their elusive nature, the tapir's role in forest ecology is important. "They are very effective seed dispersers," said Patrícia Medici, chair of the Tapir Specialist Group of the International Union for Conservation of Nature. Malayan tapirs eat about 115 different species of fruits and plants. As they roam throughout their territory, they deposit the undigested seeds in their dung. "We know that the absence of tapirs has a huge impact on the diversity and structure of the forest," Medici said.

Tracking tapir occupancy

Researchers have been using camera traps to track everything from tigers to poachers, so thousands of them are installed across Southeast Asia. Linkie and his thirty-six colleagues needed to narrow down the most likely sites. Since Malayan tapirs prefer the dense jungle understory, the researchers analyzed data from the NASA Space Shuttle Radar Topography Mission, revealing elevation and slope of the land. Other data were used to indicate forest and river edges. They also looked at forest fire data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument that could serve as a proxy for deforestation to decide whether certain trap sites might hold tapirs.

To map human activity, Linkie used the Human Footprint Index. Linkie had never used the index before, but it is well known within conservation circles, he said. Archived at the NASA Socio-

Researchers relied on 1,128 camera traps like these to gather photos of animals in the forests. Although most of the traps were set to catch tigers, they also caught tapirs and other animals that used the same trails. (Copyright J. Holden/ Fauna & Flora International)

economic Data and Applications Center, the index features human population densities and elevations, land use, travel routes, villages, and coasts. The higher the index, the more human disturbance there is. "When you look at patterns of change around these landscapes," Linkie said, "they all tend to emanate out of these areas with higher index, meaning areas that might be at lower elevation, might be closer to roads, or might be closer to villages."

After choosing nineteen sites containing a total of 1,128 camera traps, Linkie looked for tapirs in photographs taken between 1997 and 2011. The sites spanned protected conservation parks
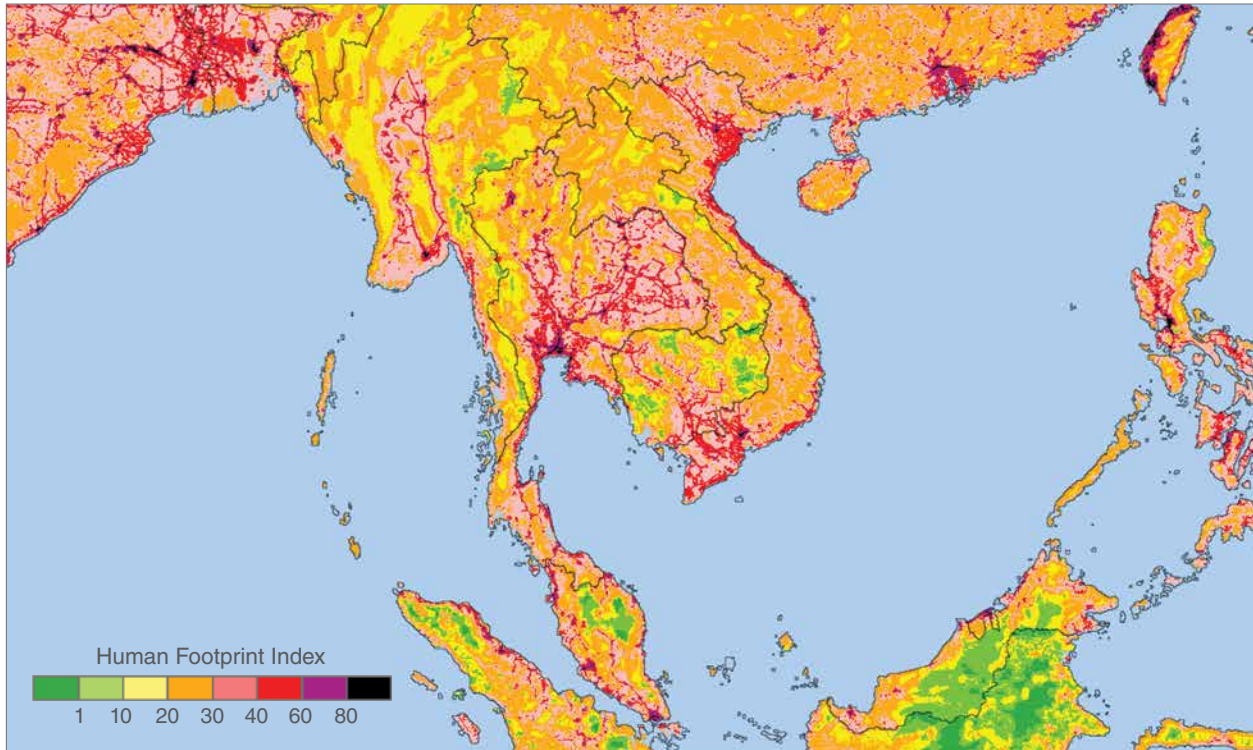
The Global Human Footprint index maps anthropogenic impacts on the environment on a scale of 0 to 100, with 0 representing the least influenced and 100 indicating the most influenced. Factors include population density, land use and infrastructure, nighttime lights, and access routes such as coastlines, roads, railroads, and rivers. Scientists often use these data for wildlife conservation planning and natural resource management. (Courtesy NASA Socioeconomic Data and Applications Center)

The skyrocketing demand for palm oil is devouring land in Malaysia and Sumatra. Oil palm plantations are replacing huge swaths of native vegetation, which further fragments forests. Malayan tapirs have few natural predators, so this fragmentation may be their biggest threat. Medici said, "They need the landscape between forest fragments to be permeable, so they can cross the landscape between forest fragments. Otherwise, these very, very small populations just don't survive." Roads, clear cuts, and plantations tend to create non-permeable landscapes that tapirs tend to avoid crossing, but permeable landscapes contain vegetation that tapirs are comfortable moving through, effectively bridging fragments.

For the first time, researchers have solid data about where the Malayan tapir currently exists and where human encroachment has already done the most damage. "Before the study, we had just a series of polygons on the map showing where people or experts saw tapirs, where tapirs occurred," Linkie said. "Now we actually have another layer of data on a threatened species that you can take to government partners." This information can help conservation groups identify priority areas for tapirs and guide decisions about where to focus future efforts.

A conservation bright spot

The tapir's very ordinariness is part of its saving grace. "Tapirs are not valued in traditional medicine, so that affords them an extra level of protection," Linkie said. And unlike tapirs in Latin America, Malayan tapirs are rarely hunted for their meat. "Hunters in Sumatra or Malaysia say the meat tastes really bad," he said. In addition, most of Sumatra's population follows Islam, which prohibits eating pig. "When it comes to tapir, many people are not quite sure

and unprotected areas in Myanmar, Thailand, Malaysia, and the Indonesian island of Sumatra. It was impossible to tell whether the traps captured snapshots of different tapirs each time or the same tapir over and over. But what the photographs could show was overall tapir "occupancy," revealing which areas tapirs occupied, and which they did not.

A new layer of data

Linkie found tapirs at 295 camera traps, which yielded a probability of occurrence of 0.43, meaning tapirs existed at 43 percent of the range-

wide study area. He also discovered a relationship between occupancy and human impacts. Overall, tapirs were less likely to exist in areas with more human disturbance. In Myanmar, occupancy rates tended to be lower, because much of the land contains open mines or is illegally logged. Trap sites in Malaysia, Thailand, and Sumatra, however, revealed less human encroachment and more robust tapir populations.

Yet even in some of the protected areas, logging and road building have destroyed or fragmented forests, isolating already small tapir populations.

what a tapir is, whether it's a pig or a horse," Linkie said. "So people generally tend to leave it alone because of that."

Linkie's research emphasized how and where the Malayan tapir may be most threatened right now, but also revealed a bright spot for its future. Given the land use changes across Southeast Asia over the past few decades, especially with the surging appetite for palm oil, Linkie did not expect to find tapirs in so many places. "Yet tapir occupancy is still quite high in a lot of these areas. That was the encouraging message from our study." By combining human activity with terrain to locate suitable camera trap sites, Linkie demonstrated that researchers can now keep tabs on what used to be an elusive animal.

To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/trapping-tapirs.

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References

García, M. J., E. P. Medici, E. J. Naranjo, W. Novarina, and R. S. Leonardo. 2012. Distribution, habitat and adaptability of the genus *Tapirus*. *Integrative Zoology* 7(4): 346–355, doi:10.1111/j.1749-4877.2012.00317.x.

Linkie, M., G. Guillera-Arroita, J. Smith, et al. 2013. Cryptic mammals caught on camera: Assessing the utility of range wide camera trap data for conserving the endangered Asian tapir. *Biological Conservation* 162: 107–115, doi:10.1016/j.biocon.2013.03.028.

NASA Land Processes Distributed Active Archive Center (LP DAAC). Burned Area Monthly L3 Global 500m. USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD, doi:10.5067/MODIS/MCD45A1.006.

NASA Land Processes Distributed Active Archive Center (LP DAAC). NASA SRTM Products. USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD.

Sanderson, E. W., M. Jaiteh, M. A. Levy, K. H. Redford, A. V. Wannebo, and G. Woolmer. 2002. The human footprint and the last of the wild. *Bioscience* 52(10): 891–904, doi:10.1641/0006-3568(2002)052[0891:THFATL]2.0.CO;2.

Wildlife Conservation Society - WCS, and Center for International Earth Science Information Network - CIESIN - Columbia University. 2005. Last of the Wild Project, Version 2, 2005 (LWP-2): Global Human Footprint Dataset (Geographic). Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). http://dx.doi.org/10.7927/H4M61H5F. http://sedac.ciesin.columbia.edu/data/set/wildareas-v2-human-footprint-geographic.

About the data

Satellites			Terra and Aqua
Sensors		Shuttle Radar Topography Mission (SRTM)	Moderate Resolution Imaging Spectroradiometer (MODIS)
Data sets	Global Human Footprint (Geographic), v2 (1995-2004)	SRTM Global 1 arc second SRTM Global 3 arc seconds	Burned Area Monthly L3 Global 500m (MCD45A1)
Resolution	1 kilometer	1 and 3 arc seconds	500 meter
Parameters	Human population, land cover, land use	Elevation	Fire and thermal anomalies
DAACs	NASA Socioeconomic Data and Applications Center (SEDAC)	NASA Land Processes DAAC (LP DAAC)	NASA LP DAAC

The burned area data used in this study were obtained through University of Maryland's MODIS Active Fire and Burned Area Products Web site.

About the scientists

Matthew Linkie is the regional conservation and development adviser for the nongovernmental conservation organization Fauna & Flora International (FFI). He is also an honorary research fellow at the University of Kent. His work primarily focuses on tiger conservation, building the scientific capacity of FFI's field staff, and providing technical support, such as for monitoring tropical wildlife, and fund raising. FFI supported his research. (Photograph courtesy M. Linkie)

Patrícia Medici is a conservationist and the chairperson of the Tapir Specialist Group of the International Union for Conservation of Nature Species Survival Commission. Her research interests include tapir conservation, tropical forest conservation, landscape ecology, and communication. The Instituto de Pesquisas Ecológicas supported her research. (Photograph courtesy M. Klink)

For more information

NASA Land Processes Distributed Active Archive Center (LP DAAC)
https://lpdaac.usgs.gov

NASA Socioeconomic Data and Applications Center (SEDAC)
http://sedac.ciesin.columbia.edu

Winter blooms in the Arabian Sea

"Why was this organism appearing in such large quantities?"

Joaquim Goes
Lamont-Doherty Earth Observatory

by Natasha Vizcarra

Two strange things unfolded in the Arabian Sea in the winter of 2003. Joaquim Goes, an oceanographer and remote sensing expert, studied satellite images of summer algal blooms when he thought to check winter blooms. The amount of algae astounded him. Then, Goes' colleagues found themselves sailing their research vessel through slushy, green waters. They took samples and sent word to Goes. "It was an organism called *Noctiluca scintillans*," Goes said. "It's never been seen in the Arabian Sea."

Noctiluca is a kind of microalgae, or tiny plant-like organism. Sailors call them sea sparkles because they glimmer at night. From space, they appear like most algae—emerald green swirls in cobalt blue seas. Under the microscope, they look like transparent, quivering balloons with whip-like tails. The green blooms could have been *Noctiluca* or other species of algae like diatoms,

A bloom of *Noctiluca scintillans* turns water into green slush off the coast of Oman. (Courtesy K. Al-Hashmi)

cyanobacteria, or coccolithophores. Whatever it was, Goes was intrigued. "Why was this organism appearing in such large quantities?" he said. "And why was it happening in the Arabian Sea?"

Much ado about algae

Algae range from minute organisms to billowy, underwater forests of kelp. But in the algal pecking order, size is not king. One-celled algae, known as phytoplankton, form the base of the ocean's food chain. Minute cyanobacteria and coccolithophores drift on the ocean's sunlit surface, converting carbon dioxide (CO_2) and water into high-energy compounds through photosynthesis. Larger phytoplankton like diatoms and dinoflagellates photosynthesize too and feed on nutrients floating nearby. These phytoplankton are gobbled up by small sea animals, or zooplankton, which are in turn eaten by larger fish and sea creatures.

In a bigger role, phytoplankton produce half of Earth's oxygen. They also suck CO_2 from the atmosphere and sequester it into the ocean depths when they die and sink. Annually, phytoplankton absorb 20 percent more carbon than the world's forests. A small change in phytoplankton growth can affect the global carbon cycle.

Scientists are particularly interested in phytoplankton blooms that grow out of control. Harmful blooms produce toxins that can kill marine animals and poison humans. Goes and biological oceanographer Helga do Rosario Gomes have been studying blooms in the Arabian Sea, a pirate-infested stretch of water northwest of the Indian Ocean bound by the Horn of Africa on the west, Pakistan in the north, and India in the east. They monitor these using data from the Moderate Resolution Imaging Spectroradiometer (MODIS), a satellite sensor that detects changes
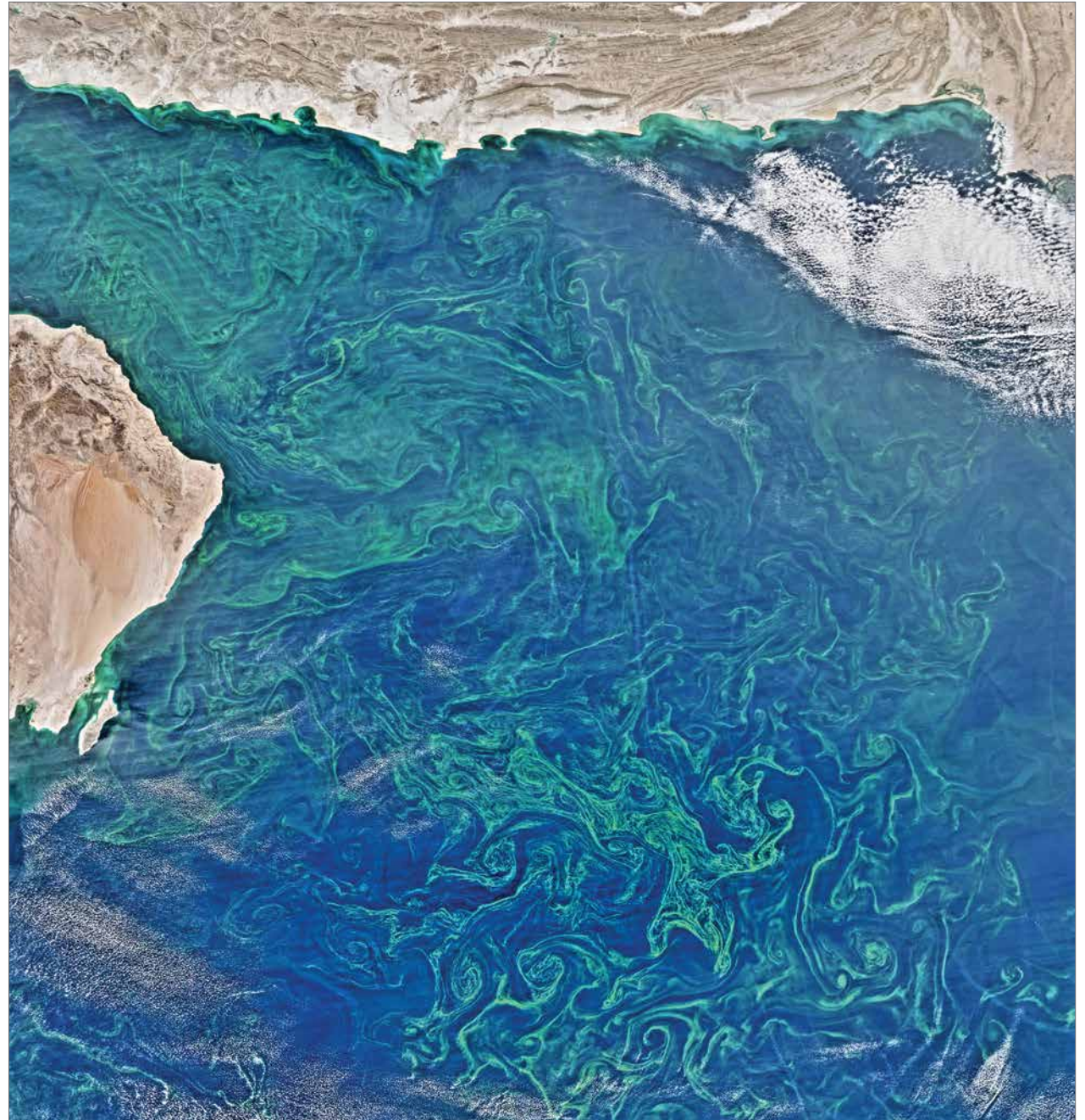
Filaments of phytoplankton twist and curl in the Arabian Sea near the coasts of Oman, Iran, and Pakistan. This February 14, 2015 image was acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) flying on the NASA Aqua satellite. (Courtesy N. Kuring/NASA Ocean Color Web)

A researcher collects a sample of seawater from a *Noctiluca scintillans* bloom in the northern Arabian Sea. (Courtesy J. Goes)
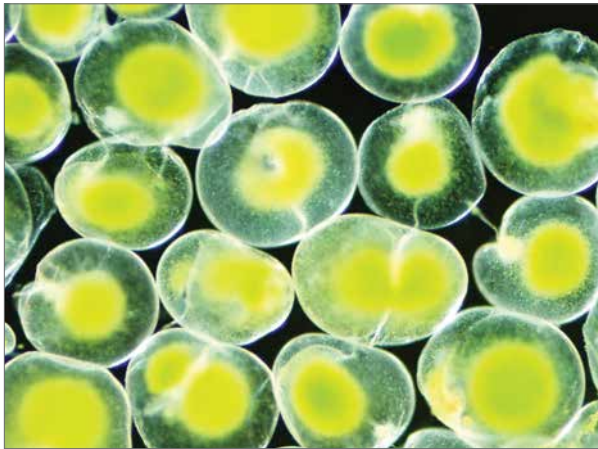
Noctiluca scintillans, a species of one-celled phytoplankton, are shown in this magnified image. Unlike most phytoplankton, *Noctiluca* are not capable of photosynthesis. They survive by trapping smaller phytoplankton with their whip-like flagellum and flushing them into their gullets. Otherwise, they grab free energy from millions of green phytoplankton living within their cell walls. (Courtesy K. Al-Hashmi)

in the green pigment chlorophyll, present in all plants and essential in photosynthesis.

In the summer of 2003, satellites detected that the sea was crazy with photosynthetic action. "The Arabian Sea's productivity was rapidly increasing," Goes said. The researchers found that intense southwest monsoon winds caused the summer uptick in phytoplankton.

Shrinking snowcaps in the Himalaya caused the Indian subcontinent to become warmer than usual in the summer. This formed an intense low-pressure area over the subcontinent, which sucked in a stronger southwest wind from the Arabian Sea. These winds then generated strong upwelling near the coasts of Yemen and Oman, drawing colder, nutrient-rich water from the depths to the surface. The influx of nutrients overfed phytoplankton, causing populations to explode.

Winter was another story. "The Himalayan snowcap was shrinking and winter winds were also warmer and more humid," Gomes said. "We thought winter convective mixing should have been decreasing along with phytoplankton populations." But satellite data showed these conditions had the opposite effect on phytoplankton. Something else was causing the burgeoning winter blooms.

An ominous switch

Beginning in 2009, Goes and Gomes spent three winters on the research vessel *Sagar Sampada*, sailing off the coast of Goa transecting through blooms in the northern Arabian Sea. The satellites were indeed seeing *Noctiluca*, the green kind that lives in tropical waters. Red *Noctiluca* lives in temperate waters. The researchers monitored satellite data, collected bloom samples, and

performed shipboard experiments, which led to more questions than answers.

Goes and Gomes collaborated with NASA oceanographer Jeremy Werdell on an algorithm to detect green *Noctiluca* blooms in MODIS data. "Since they were first detected in the early 2000s, blooms of the green *Noctiluca* now occur every year with predictable regularity from January to March," Gomes said. According to historical records and other research missions, diatoms dominated the Arabian Sea before 2000. Khalid Al-Hashmi, a researcher at Oman's Sultan Qaboos University, said there were sporadic *Noctiluca* sightings in the 1950s and 1980s, but only along India's western coast. Goes said, "Within a decade, *Noctiluca* had totally replaced diatoms at the base of the Arabian Sea's food chain."

This does not bode well for the region's fishermen. Zooplankton have no trouble eating diatoms but cannot eat *Noctiluca* because they are too big. If zooplankton starve and die, larger creatures up the food chain are compromised. Shipboard experiments confirmed that *Noctiluca* were indeed outcompeting the diatoms. "They were short-circuiting the food chain," Goes said. Only jellyfish, sea salps, and turtles can feed on *Noctiluca*, so this trend could upend the Arabian Sea's fishing industries.

The researchers also noticed that blooms coincided with hypoxic seawater, or water low in oxygen. "Big cities in India and the Middle East release lots of sewage water into the Arabian Sea. Nitrogen and phosphorus from agricultural runoff contribute to a decrease in seawater oxygen concentration, causing the spread of hypoxia," Goes said. The researchers checked historical archives again to see past levels. "We saw a trend
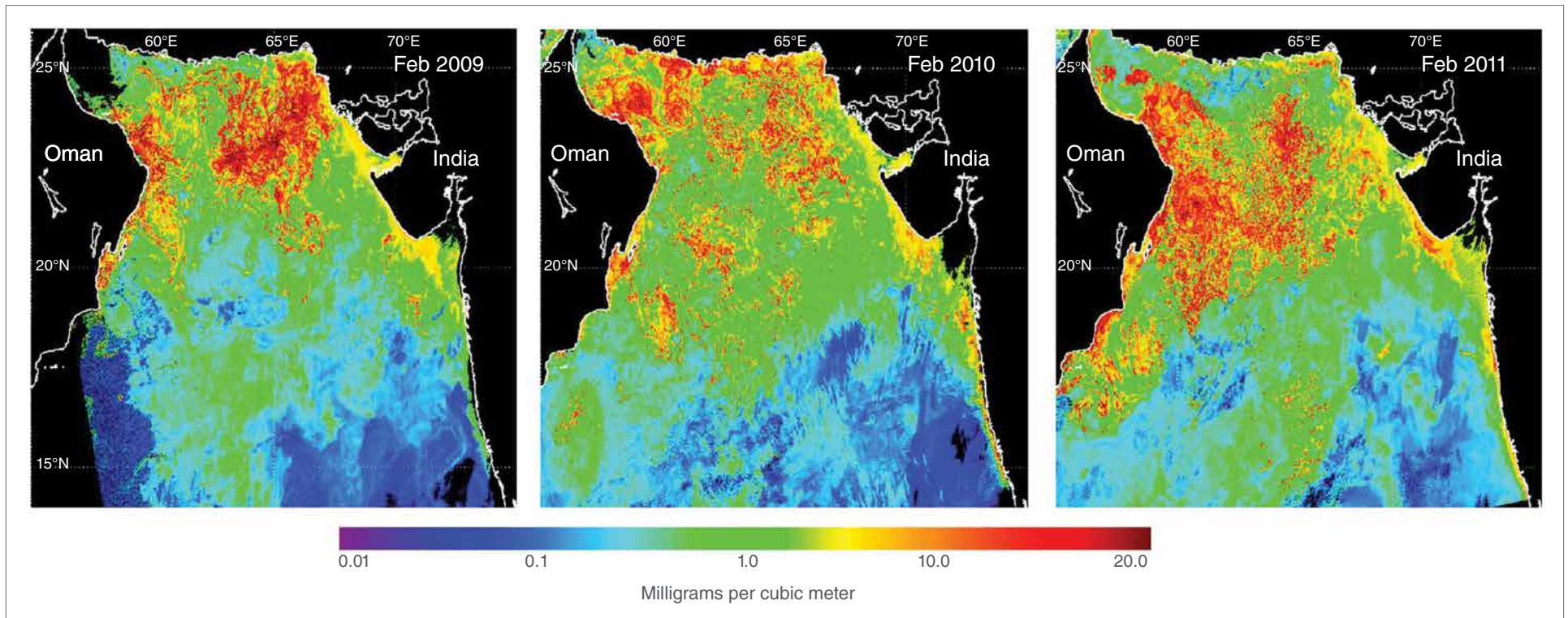
These images show February phytoplankton blooms in the Arabian Sea, dominated by *Noctiluca scintillans*, for (a) 2009, (b) 2010, and (c) 2011. Data are in milligrams per cubic meter, and are from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the NASA Aqua satellite. (Courtesy Gomes, H., et al., 2014, *Nature Communications*)

of rapid decreases in oxygen concentration in the last seven years," Goes said. The trend roughly coincided with the switch from diatoms to *Noctiluca*, so they suspected the two were connected. But how?

In the dead zone

In hypoxic waters, slow-moving creatures like crabs and lobsters do not stand a chance. Fish fall unconscious and suffocate. These biological dead zones form when phytoplankton feast on a flush of nutrients and reproduce dramatically. Huge populations of bacteria need oxygen to metabolize the waste as well as the dead phytoplankton sinking from the sea surface. "In the process,

they strip the water of oxygen," Goes said. Water circulation is sluggish in the Arabian Sea, so oxygen-starved water does not get replaced as fast as it does in the Pacific or Atlantic Oceans.

But the connection between hypoxia and the phytoplankton switch did not make sense. Diatoms need CO_2, not oxygen, for photosynthesis. *Noctiluca* eat smaller phytoplankton which also only require CO_2. So the researchers took a closer look at how the two organisms behave in hypoxic conditions.

In the ship lab, the researchers transferred *Noctiluca* and its diatom competitors into air-

tight bottles of oxygen-starved seawater. They looked at how well the organisms converted CO_2 to energy—a way to measure productivity. *Noctiluca*'s rate rose by 300 percent, while the rate of the diatoms' fell by nearly as much. "*Noctiluca* just did better," Goes said. "It started growing faster." They also found that *Noctiluca* grew faster in light than in the dark, thanks to millions of sun-loving endosymbionts living within its cell walls.

The endosymbionts seem key to *Noctiluca*'s advantage. These are smaller phytoplankton that convert CO_2 to energy by photosynthesis and pass the energy on to *Noctiluca* like rent. It is

Colorful parrot fish lie with other species on a fishmonger's mat in Muscat, Oman. (Courtesy T. Schmurr)

additional food for *Noctiluca*, which are not capable of photosynthesis and usually feed on other phytoplankton, zooplankton eggs, and decaying organic particles in seawater.

"This endosymbiont evolved 1. 2 billion years ago in an atmosphere that was rich in CO_2 and low in oxygen," Goes said. "We think that it conserved this gene for photosynthesizing in a low-oxygen environment and now that hypoxic waters are coming to the surface, these genes are overexpressing themselves and allowing the Rubisco enzyme to function better."

The chief architect

Rubisco is an ancient enzyme present in all plants and responsible for the conversion of CO_2 into organic compounds. Old sedimentary rocks in Zimbabwe and Canada place its appearance 2.9 billion years ago when Earth was a much different place. Continents were still forming and stabilizing, and air was mostly CO_2. There were no plants or animals, just bacteria-like life and multicellular organisms. Somehow, Rubisco enabled Precambrian phytoplankton to capture CO_2 from the atmosphere and produce oxygen. The change was radical. Scientists have called Rubisco "the chief architect of the atmosphere."

Goes and Gomes have a hunch that the Arabian Sea's low-oxygen waters are somehow causing the Rubisco within the endosymbiont to perform better, resulting in more energy for the *Noctiluca*.

James V. Moroney, a molecular biologist at the Louisiana State University, thinks it's possible.

"Oxygen competes with CO_2 in Rubisco. If you lower oxygen, that could enhance carbon fixation in the endosymbiont," he said. Diatoms, on the other hand, have the ability to concentrate CO_2 around Rubisco to make it perform better. "Dropping the oxygen a bit shouldn't make much difference to the diatoms," he said.

Moroney does caution that not enough is known about *Noctiluca* nor its endosymbiont to draw any conclusions. Senjie Lin, an expert in phytoplankton genomics at the University of Connecticut, agrees. "Rubisco may very likely play a role here," Lin said. "But the situation may be more complex than we understand right now." Lin is analyzing the endosymbiont's RNA to see whether a gene that codes for the Rubisco enzyme is indeed responding to hypoxic conditions in the Arabian Sea.

Though the Rubisco hypothesis is fascinating, Goes and Gomes are also checking other leads. *Noctiluca* could be responding to nutrients brought by dust plumes from Iran, Afghanistan, and Pakistan. And because hypoxic waters tend to be acidic, the researchers are looking at the sea's pH levels, wondering whether acidification is also promoting the growth of *Noctiluca*.

Goes, Gomes, and their colleagues continue to chase more questions. Meanwhile, cities and populations around the Arabian Sea expand. What will the rise of *Noctiluca* bring? Will it leave a sparkling dead sea, or will it shift the food web, restructuring the ecological design of these waters?

To access this article online, please visit https://earthdata.nasa .gov/sensing-our-planet/winter-blooms-in-the-arabian-sea.

References

Al-Hashmi K., C. L. Smith, M. Claereboudt, S. A. Piontkovski, and A. R. Al-Azri. 2015. Dynamics of potentially harmful phytoplankton in a semi-enclosed bay in the Sea of Oman. *Bulletin of Marine Science* 91, doi:10.5343/bms.2014.1041.

Goes, J. I., P. G. Thoppil, H. d. R. Gomes, and J. T. Fasullo. 2005. Warming of the Eurasian landmass is making the Arabian Sea more productive. *Science* 308: 545–547.

Gomes, H. d. R., J. Goes, S. G. P. Matondkar, E. J. Buskey, S. Basu, S. Parab, and P. Thoppil. 2014. Massive outbreaks of *Noctiluca scintillans* blooms in the Arabian Sea due to spread of hypoxia. *Nature Communications* 5: 4862, doi:10.1038/ncomms5862.

Lin, X., H. Zhang, Y. Cui, and S. Lin. 2012. High sequence variability, diverse subcellular localizations, and ecological implications of alkaline phosphatase in dino-flagellates and other eukaryotic phytoplankton. *Frontiers in Microbiology,* doi:10.3389/fmicb.2012.00235.

Moroney, J. V., and R. A. Ynalvez. 2009. Algal Photosynthesis. In: *Encylopedia of Life Sciences*. John Wiley & Sons, Ltd: Chichester, doi:10.1002/9780470015902.a0000322.pub2.

NASA Ocean Biology DAAC (OB.DAAC). Level 2 Ocean Color Web. Greenbelt, MD, USA. http://oceancolor.gsfc.nasa.gov/cms.

NASA Socioeconomic Data and Applications Center (SEDAC). Gridded Population of the World (GPW), v3. Palisades, NY, USA. http://sedac.ciesin.columbia.edu/data/collection/gpw-v3.

Werdell, J., C. S. Roesler, and J. I. Goes. 2014. Discrimination of phytoplankton functional groups using an ocean reflectance inversion model. *Applied Optics* 53: 4,833–4,843, doi:10.1364/AO.53.004833.

For more information

NASA Ocean Biology Distributed Active Archive Center (OB.DAAC)
http://oceancolor.gsfc.nasa.gov

NASA Socioeconomic Data and Applications Center (SEDAC)
http://sedac.ciesin.columbia.edu

NASA Moderate Resolution Imaging Spectroradiometer (MODIS)
http://modis.gsfc.nasa.gov

Goes-Gomes Lab at Columbia University's Lamont Doherty Earth Observatory
http://helgagomes.com

About the data

Satellite	Aqua	
Sensor	Moderate Resolution Imaging Spectroradiometer (MODIS)	
Data sets	Level 2 Ocean Color Web	Gridded Population of the World
Resolution	2 kilometers	2.5 arc-minute ¼ degree, ½ degree, 1 degree
Parameters	Chlorophyll a concentration	Population density
DAACs	NASA Ocean Biology Distributed Active Archive Center (OB.DAAC)	NASA Socioeconomic Data and Applications Center (SEDAC)

About the scientists

Khalid Al-Hashmi is a researcher at Sultan Qaboos University in Muscat, Oman. His research focuses on phytoplankton ecology and biological oceanography. The Research Council of Oman supported his research. Read more at http://goo.gl/phiAr3. (Photograph courtesy K. A. S. Al-Hashmi)

Joaquim Goes is a research professor at the Lamont-Doherty Earth Observatory at Columbia University in Palisades, New York. His research focuses on the structure and function of plankton ecosystems and their response to physical forcing, and forecasting the responses of marine ecosystems to global change. NASA and the National Science Foundation supported his research. Read more at http://goo.gl/zDpvOq. (Photograph courtesy J. Goes)

Helga do Rosario Gomes is a research scientist at the Lamont-Doherty Earth Observatory at Columbia University in Palisades, New York. Her research focuses on remote sensing of climate change and its effect on ocean biogeochemistry, and how coastal megacities change the biodiversity of the Arabian Sea. NASA and the National Science Foundation supported her research. Read more at http://goo.gl/fYljWj. (Photograph courtesy H. d. R. Gomes)

Senjie Lin is a professor of marine sciences at the University of Connecticut. His research focuses on phytoplankton molecular ecology and functional genomics. The National Science Foundation and China's National Natural Science Foundation supported his research. Read more at http://goo.gl/CILXc6. (Photograph courtesy D. Buttrey/University of Connecticut)

James V. Moroney is a professor of biological sciences at Louisiana State University. His research interests focus on how plants and algae acquire the carbon dioxide they need for photosynthesis. The National Science Foundation supported his research. Read more at http://goo.gl/EMivzG. (Photograph courtesy J. V. Moroney)

Heavy weather, high seas

"Rogue waves are the needle in the haystack. You need to be either really unlucky to encounter one, or really lucky to measure one."

Val Swail
Environment Canada

by Karla LeFevre

In the winter of 1978, the merchant ship *München* set out across the Atlantic Ocean to deliver cargo to the United States. With a length of 200 meters (656 feet), the ship was one of the biggest ever built at the time and was designed to withstand intense storms and hurricanes. But on December 12 at 3 a.m., the *München* tapped out an S.O.S. Though nearly a hundred ships and planes combed the Atlantic, the *München* was never found. It was concluded that an "unknown weather-related event" caused its disappearance. Whatever the event, it was extreme.

Powerful weather systems like hurricanes generate ocean swell, which spawns waves that roll out over great distances. When rolling waves collide with surface waves, they create what scientists call very extreme sea states, the kind that scuttle ships and destroy derricks. Meteorologist Val Swail and his late colleague, meteorologist

HMS *Edinburgh* endures storm force weather in the South Atlantic. Even with 8-meter (26-foot) waves crashing against the bridge, the ship managed to sustain no damage. (Courtesy D. Rosenbaum, Royal Navy Media Archive)

Vincent Cardone, wanted to predict these very extreme sea states. If they could identify where and when heavy weather caused high seas, they might be able to prevent catastrophes like the sinking of the *München*.

A sea change

After the *München*'s demise, many speculated that a rogue wave, a monstrous wave that appears out of nowhere, was to blame. Though somewhat controversial, scientists have recently defined a rogue wave as roughly twice as high as the surrounding waves. In a very extreme sea state, where waves reach at least 14 meters (46 feet), a rogue wave could crest at nearly 28 meters (92 feet). Yet because they are inherently difficult to measure, there are only a handful of measurements of such waves in high seas.

"Rogue waves are the needle in the haystack," Swail said. "You need to be either really unlucky to encounter one, or really lucky to measure one." Instruments on the Draupner E oil platform in the North Sea captured a 25.6 meter (84.0 foot) wave in 1995. "But most rogue waves actually occur in quite low sea states where the average waves are two meters. So you get one that's four meters," Swail said. "For an oil platform that got 46 feet last week, who cares. Yes it's a rogue wave, but not an impactful one." Researchers have found that very extreme sea states, not rogue waves, destroy most ships and structures at sea.

As early as the 1960s, Cardone had been searching for new ways to measure extreme sea states. With a team at New York University, he developed the first spectral wave model, a mathematical model that attempted to predict how waves interact at different frequencies. The team created the model for the U.S. Navy using real-time

U.S. Navy Minemen 2nd Class Matthew Rishovd (left) and Kody Egelhoff make adjustments to a National Oceanic and Atmospheric Administration weather buoy in the Atlantic Ocean on January 25, 2008. (Courtesy E. Merriam/U.S. Navy/ murdoconline.net)

wind and storm data from reconnaissance flights and other naval programs like the Joint Typhoon Warning Center. For the first time, forecasting the sea state became possible.

That model not only made Navy operations safer; it helped build more seaworthy oil and gas rigs. The experience led Cardone, a former research scientist and professor, to co-found a company called Oceanweather based on providing ocean wind and wave forecasting data. Andrew Cox, president of Oceanweather, said, "Way back, if you wanted to do structure design, you looked at very extreme sea state data and maps and took an educated guess of what the wave climate would look like. This was a fundamental change in how things were done."

Model data

Then, in 1982, an oil rig off the Atlantic coast of Canada was pummeled by 190-kilometer-per-hour (100-knot) winds and waves up to 20 meters (65 feet) high. All eighty-four people on the rig died. Five more deadly oil rig accidents occurred before 1990, underscoring the need for more reliable models. Swail and Cardone found that their models performed poorly above 12 meters (40 feet). "There was something missing," Swail said. "So we said let's find a data set that can validate the models and get them to perform in these extreme cases."

One thing they were missing was better wave data. Measuring wave heights over the open ocean is challenging even today. Mariners have
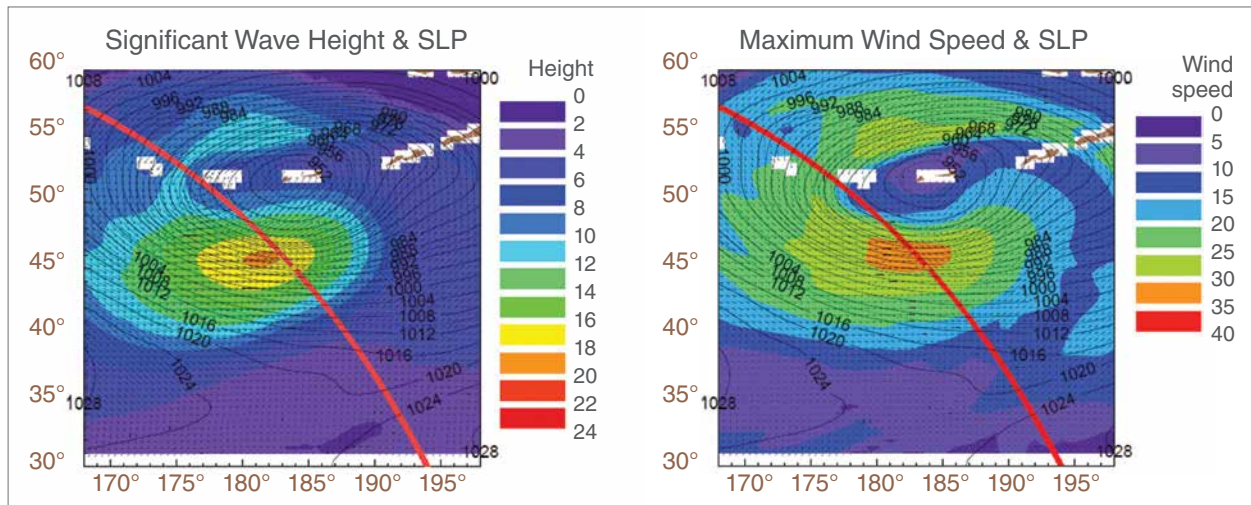
These plots show a hindcast for March 18, 1999, when a 20.6-meter (68-foot) wave crested in the North Pacific at 05:26 Coordinated Universal Time (UTC). The significant wave height (left, in meters) and maximum surface wind speed (right, in meters per second) are superimposed on isobars, lines connecting equal atmospheric Sea Level Pressure (SLP). Hindcast measurements are from Climate Forecast System Reanalysis (CFSR) data, TOPEX/Poseidon satellite data, and GROW2012 model data. (Courtesy A. T. Cox)

traditionally reported their observations of wave heights to the National Weather Service, but these are fairly subjective. Wave recorders mounted on ships and buoys also have their limits. Cardone's colleagues found that the recorders on ships are only reliable for waves up to 9 meters (30 feet), and buoys are moored along coasts, far from the open ocean.

Satellites soon provided a better way to gather wave data, but there was one drawback: the many different algorithms used in processing made the data unwieldy. GlobWave, a database of altimeter data from seven satellites, solved this problem. It applied a single algorithm to the data from all satellites. Radar altimeter measurements from Poseidon/TOPEX and Jason-1, available at the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC), were used to build the database. They finally had a consistent

record of extreme wave data, and it validated their models.

Separating truth from tale

When they combined that record with a global wave model from Oceanweather called GROW2012, the results confirmed their suspicions. The model spanned thirty-three years and included wind and wave data from many sources, such as satellites, visual observations, buoys, and wave recorders. "We saw things that surprised some people, but they weren't that surprising to us," Swail said.

With GlobWave, they sorted through more than 5,000 instances of extreme sea conditions where waves were higher than 12 meters (39 feet). They found the highest average waves were more than 18 meters (59 feet) and occurred in the North

Atlantic and North Pacific oceans, with more than twice the number occurring in the North Atlantic. Just three had a peak slightly higher than 20 meters (66 feet). In the Southern Ocean, where sailors have dubbed the latitudes from 40 to 70 degrees south the "Roaring Forties," "Furious Fifties," and "Shrieking Sixties" due to high winds and large waves, only three peaks were higher than 18 meters (59 feet).

"We were able to verify that the average wave climate in the Southern Ocean is higher, but the extreme wave climate is not as severe as the North Pacific or even parts of the Pacific," Swail said. They also verified something ship builders have long known. Swail said, "Because of the land masses to the west and the strong storm formation there, the North Atlantic is the most extreme wave climate in the world." For more than a century, in fact, ship design classification societies have used visual observations from the North Atlantic as the basis for design.

Ship rerouting

Still, the question remained: What was the risk that a vessel like the *München* would encounter catastrophic waves? Cardone called on Henry Chen, a researcher at Jeppesen Marine. Like Cardone, Chen routed ships for a living. Together they created a software program called TowSim. Cox said, "TowSim simulates a ship leaving a port every three or six hours and, as it travels on its route, it picks up global wind and wave information from GROW2012. So we'll get companies towing large structures who need to know what the conditions are along the route."

With TowSim, their research showed that the probability of sea states to cause catastrophic damage over thirty-three years is surprisingly

small. On average, a ship could be exposed to extreme sea states for only about three hours on six of the nine routes and up to ten hours on two of the routes, they found.

They also noted that the chances that seas would swell to make monster waves were highest in the North Atlantic and North Pacific during winter, especially December, putting the *München* in exactly the wrong place and time. The most treacherous routes were along the great circle between the midsection of U.S. East Coast and the entrance to English Channel, and from Yokohama to Seattle.

Their work has made ship routing safer, and it has become the basis for structure design in the offshore oil and gas industry. Perhaps most importantly, it has advanced very extreme sea state modeling so more improved models can follow. Cox said, "We can now test our models in these most extreme storms to make sure the physics are appropriate all the way up into the high extent that we can measure."

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References

Cardone, V. J., B. T. Callahan, H. Chen, A. T. Cox, M. A. Morrone, and V. R. Swail. 2015. Global distribution and risk to shipping of very extreme sea states (VESS). *International Journal of Climatology* 35(1): 69–84, doi:10.1002/joc.3963.

JASON-1. 2008. Jason-1 Altimeter Geophysical Data Record (GDR) NetCDF. Ver. 1. PO.DAAC, CA, USA.

NASA/JPL/PODAAC. 1998. TOPEX/POSEIDON Altimeter Merged Geophysical Data Record Generation B. Ver. B. PO.DAAC, CA, USA. http://dx.doi .org/10.5067/TPMGD-BIN0B.

About the remote sensing data

Satellites	TOPEX/Poseidon	Jason-1
Sensors	TOPEX-A TOPEX-B Poseidon-1 Radar Altimeters	Poseidon 2 Radar Altimeter
Data sets	Level 2 TOPEX/Poseidon Altimeter Merged Geophysical Data Record Generation B (MGDR-B)	Level 2 Altimeter Jason-1 Geophysical Data Record (J1 GDR)
Resolution	11.2 kilometer (Along-track) x 5.1 kilometer (Across-track)	11.2 kilometer (Longitude) x 5.1 kilometer (Latitude)
Parameters	Significant wave height	Significant wave height
DAACs	NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC)	NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC)

About the scientists

Vincent J. Cardone was a meteorologist and co-founder of Oceanweather, Inc. His research included tropical meteorology and ocean modeling, with a focus on developing and implementing spectral wave models. The National Science Foundation supported his research. Read more at http://goo.gl/ B8N2pM. (Photograph courtesy A. T. Cox)

Andrew Cox is a meteorologist and the president of Oceanweather, Inc. His research interests include tropical meteorology, ocean wave modeling, remote sensing, and the generation of long-term wind and wave climatologies for operability and structure design. The National Science Foundation supported his research. (Photograph courtesy A. T. Cox)

Val Swail is a meteorologist and emeritus scientist in Environment Canada's Climate Research Division. His research interests include long-term climate trend and variability for marine climatology, particularly wind, waves, and storm surges. The Canadian Program of Energy Research and Development supported his research. Read more at http://goo.gl/VC9LQY. (Photograph courtesy V. R. Swail)

For more information

NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC)
http://podaac.jpl.nasa.gov

Heart of drought

"Long-term drought will likely change the structure and composition of the forest."

Liming Zhou
University at Albany

by Agnieszka Gautier

In 1890, traveling on a steamer for a Belgian trading company, a young Joseph Conrad pierced the heart of darkness. As the mighty brown current of the Congo River uncoiled, he drifted into the depths of a colossal jungle that dripped with steam and glistened under the sun. Dense vegetation unfurled. "[It stood] higher than the wall of a temple," he would later write in his novella, *Heart of Darkness*, in which nature is as much revered as it is suspect. The tale, set in the Congo Rainforest and centered on an isolated ivory trading post, is steeped with the horrors

A mountain gorilla nestles within dense vegetation in the Mgahinga Gorilla National Park in Uganda. The park covers the northern slopes of three volcanoes in the Virunga Mountains, which are home to a large variety of wildlife, including about half the world's critically endangered mountain gorillas. (Courtesy W. White)

Conrad witnessed, securing his disillusionment with imperialism.

More than a century later, the region still struggles against the avarice of exploiters ready to strip the rainforest of minerals, ivory, and oil. "The region's political instability continues to be a reason we've had to depend on satellite observations," said Philippe Ciais, a scientist at the Laboratoire des Sciences du Climat et de l'Environnement in France. Unlike the Amazon rainforest, the Congo rainforest lacks in situ observations and resources for field study. Any first-hand accounts are precious.

Conrad described the Congolese foliage as "so dark-green as to be almost black." But the mighty jungle, according to a recent study, shows that deep green beaten back not by man, but by drought.

Beyond the spotlight

Halfway around the world, the Amazon rainforest experienced severe drought in 2005 and 2010 with record low rainfall, drying tributaries, cracking soil, and collapsing trees. It got press. "We pay so much attention to the Amazon rainforest and so little to the African rainforest," said Liming Zhou, a researcher at University at Albany. Though effectively less dramatic, an earlier study, examining precipitation rates from 1960 to 1998, alerted Zhou to a decades-long drought in the Congo Basin. Zhou then analyzed gauge and satellite data from 1950 to 2012 and found persistent drying beginning in 1985. Rainfall also reached its lowest levels in the last decade. No trees came crashing down, but Zhou wanted to know if the thirty-year drought had an effect. "This is the first study to link long-term drought to tropical rainforests," Zhou said.


Rays of sunlight break up a downpour in the Congo. (Courtesy A. Thiel)

The Congo rainforest shelters all species of gorilla, the bonobo—a more-peaceful, pygmy cousin of the chimpanzee—the forest elephant, and the shy okapi. It is home to more than 10,000 species of tropical plants, with 30 percent unique to this region. Large herbivores, feeding on smaller trees, shape a canopy of thicker and taller trees than in the Amazon rainforest. Between 250,000 to 600,000 indigenous people live here. The Congo basin stands as the second largest rainforest after the Amazon; it spans six countries, and contains a quarter of the world's remaining tropical forest. So a drop in plant photosynthetic capacity, even a minor one, would have implications on local biodiversity and the global carbon cycle.

"Before our study, some suggested the African rainforest may be insensitive to drought," Zhou said. With higher altitudes and more semi-evergreen trees, the Congo rainforest is cooler than the Amazon rainforest. It is also drier. "Researchers thought maybe it already adapted to a drier climate," Zhou added.

Short, intense droughts lasting less than six months are easy to detect. Rivers dry up. Vegetation shrivels and dies, resulting in erosion and dust bowls. Odds for fire increase. Longer-term droughts, technically more than six months—but stretching into decades—exhibit subtler effects that last longer and are potentially harder to

Regional Mean Rainfall Anomaly (1950-2012)
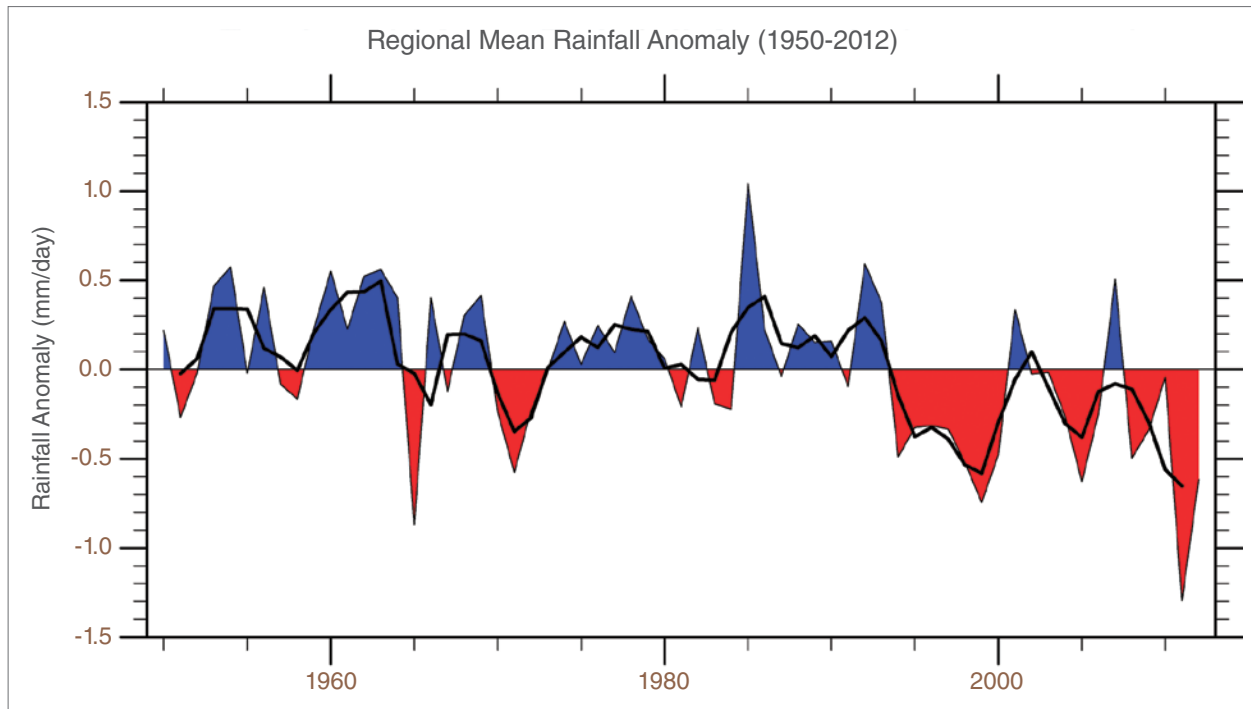
This graph shows mean rainfall anomalies (millimeters per day) in April, May, and June for the period 1950 to 2012, averaged over the intact Congo rainforest (6°S to 5°N, 14° to 31° E). The solid line represents three-year average rainfall anomalies. The data are from the Global Precipitation Climatology Centre. (Courtesy L. Zhou)

The top image shows overall forest cover for the Congo Basin, the majority of which lies in the northern area of the Democratic Republic of the Congo (DRC). Gray lines define borders with the DRC in center, the Congo to the left, and Uganda, Rwanda, and Burundi to the right. The bottom image shows spatial patterns of change in April–May–June vegetation greenness for the period 2000 to 2012. Data are from the Enhanced Vegetation Index (EVI), derived from the Moderate-Resolution Imaging Spectroradiometer (MODIS). (Courtesy L. Zhou)

reverse. Land may sink from parched aquifers. Coastal regions may suck saltwater inland. In the case of the Congo, the full effects are yet to be determined, but the rainforest is beginning to take notice.
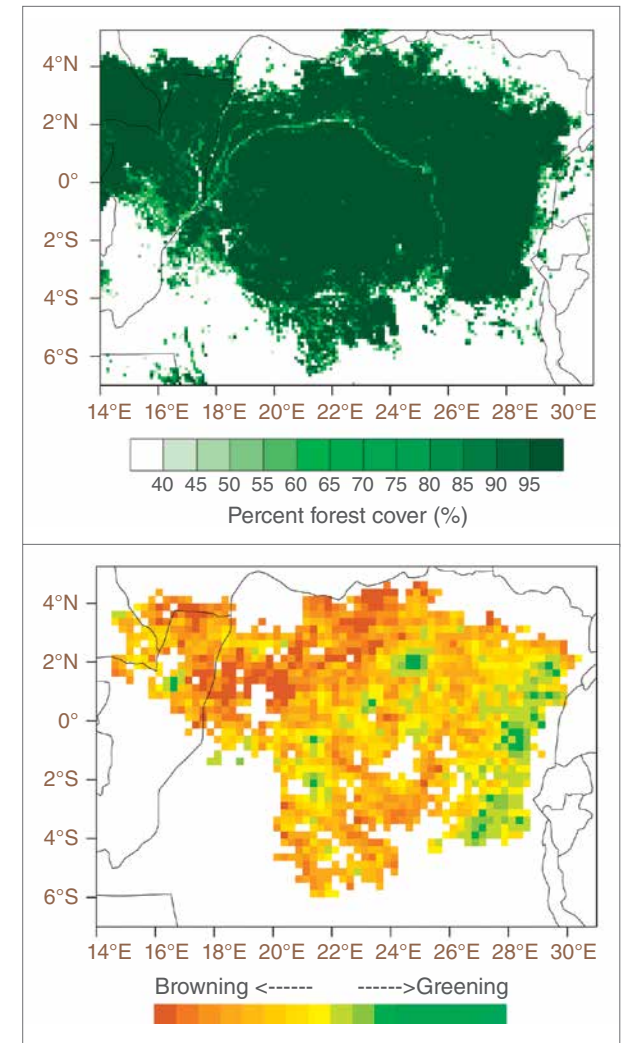
Using data from several satellites, primarily covering 2000 to 2013, Zhou and his colleagues analyzed a region in the Congo Basin with a low deforestation rate. Specifically, the team analyzed vegetation greenness data, a way to measure the health of plants and trees. Simply put, was the forest responding to the drought, and if so, how?

"No one has done a focused analysis like this," said Ciais, who helped analyze the data. "Seeing the data was surprising." Vegetation greenness experienced widespread decline. Patches of brown splattered throughout satellite images. The sensor at the center of it all is called the Moderate Resolution Imaging Spectroradiometer (MODIS). It flies on the NASA Terra satellite, able to capture and measure both plant growth and atmosphere and cloud properties on a global scale.

The science of green

By observing different wavelength absorptions versus reflections, scientists are able to quantify plant photosynthetic capacity. The more visible light is absorbed, the busier the plant. Chlorophyll, a green pigment within plants, is an agent in photosynthesis. Visible light feeds

photosynthesis, transforming light energy into a sugar that further releases energy through its consumption. Virtually all energy used by a living organism stems from this transformation of sunlight to sugar.

Browning occurs when plants are stressed by a lack of water. The plump water cells within leaves wither, and the plant becomes less productive. If the stress is beyond some threshold, trees may even drop their leaves. But what is that threshold?

The Normalized Difference Vegetation Index (NDVI) is an algorithm that uses the different wavelengths of light reflected by vegetation to map the greenness of the world. Zhou's study also used the MODIS-based Enhanced Vegetation Index (EVI) with its finer detail, making it more sensitive to differences within dense vegetation. The team focused on a three-month period from April to June, peak rain and growing seasons, because it shows the highest percentage of high-quality EVI pixels and the least cloud obstruction. From 2000 to 2012, EVI declined over 92 percent of the studied area, with about 40 percent showing a significant negative trend.

To make sure the results were sound, Zhou used multiple satellites. "It's good to get field observations to see what is happening but in this case we can't," Zhou said. "So we used lots of satellites. Each kind of remote sensing technology is different, so you can look at the same area with different information."

The Tropical Rainfall Measuring Mission (TRMM), a sensor that monitors tropical precipitation, verified a decline in rainfall for the thirteen-year period. But even with less water coming down, could the rainforest adapt in how

The shy, endangered okapi rests under the canopy of the Ituri Rainforest, located in the northeastern Democratic Republic of Congo, formerly Zaire. With its stripes, the okapi resembles the zebra, but it is most closely related to the giraffe. A 2013 study determined that 10,000 okapis remain in the wild, down from 40,000 a decade ago. (Courtesy R. Stowe)

it stores and accesses water? Could deep roots even reach ground water? To check, the scientists turned to another mission, the Gravity Recovery and Climate Experiment (GRACE), twin satellites that detect gravity anomalies by sensing subtle changes in Earth's mass. Using GRACE data, Zhou calculated total water storage changes in the area's wetlands, rivers, ground water, and soil moisture to determine where the storage changed. GRACE confirmed a decline in groundwater levels, further stressing plant productivity.

From the ground up, Zhou shifted to the atmosphere. Cloud cover and aerosol particles influence

About the remote sensing data			
Satellites	Terra	Terra and Aqua	Tropical Rainfall Measuring Mission (TRMM)
Sensors	Moderate Resolution Imaging Spectroradiometer (MODIS)	MODIS	Precipitation Radar Microwave Imager
Data sets	Gridded Atmospheric Product (MOD08_M3)	Vegetation Indices (MOD13C2) Land Surface Temperature and Emissivity (MYD11C3) Land Cover Type (MCD12C1)	TRMM Multi-Satellite Precipitation Analysis
Resolution	1 degree	5.6 kilometer	0.25 x 0.25 degree resolution
Parameters	Aerosol optical thickness (AOT) Cloud optical thickness (COT)	Normalized Difference Vegetation Index Enhanced Vegetation Index Temperature Emissivity Land cover types	Precipitation
DAACs	NASA MODIS Level 1 and Atmosphere Archive and Distribution System Distributed Active Archive Center (MODAPS DAAC)	NASA Land Processes DAAC (LP DAAC)	NASA Goddard Earth Sciences DAAC (GES DAAC)

the rate of photosynthetic productivity. To assess these changes, Zhou used MODIS aerosol optical thickness (AOT) and cloud optical thickness (COT) values. AOT measures the degree of solar light interference. Higher aerosols result in lower visibility and less sunlight reaching vegetation. COT determines the thickness or transparency of cloud cover. Could a change in either confirm drought? From 2000 to 2012, AOT barely changed, but COT showed significant decrease. With thinner clouds, more unobstructed sunlight touches the surface. More sunlight is good for photosynthesis, but the process also transpires water out. A boost in transpiration may empty all moisture out of the soil, causing another level of stress on vegetation.

Another pair of eyes

The persistent browning of the Congolese forests may reflect a slow adjustment to the long-term drying trend. It is nature's way of coping. In the short-term, proper rainfall offers recovery. "But long-term drought will likely change the structure and composition of the forest," Zhou said. For example, species in the Ghanaian forest shifted from wetter vegetation to favor deciduous trees and a drier canopy after a twenty-year drought.

But detection of such impacts requires long-term ground observations, similar to the Amazon. "People can't expect North American researchers to study the Amazon rainforest or European researchers to study the African rainforest," Ciais said. "In the end, it has to be local entities that take charge of field observations." The political situation continues to undermine much-needed science. For instance, Africa's oldest national park, the Virunga National Park, battles with political instability and foreign corporations. In the last twenty years, the park has lost more than 150 rangers protecting one of the largest mountain gorilla populations. For the Congo Basin to

be better understood, scientists need to be able to make proper field observations, but that can only happen when the political situation offers the African people security.

"Though we don't have ground observations, the satellite data shows almost everything is impacted," Zhou said. With climate models shaping a future with more frequent droughts, the impact of browning on the carbon cycle and biodiversity conservation needs further study. "It should become a research priority," Zhou added. Because as this study suggests, it is not a matter of whether the rainforests will respond, but more a question of how.

To access this article online, please visit https://earthdata.nasa .gov/sensing-our-planet/heart-of-drought.

About the remote sensing data, continued

Satellites	Gravity Recovery and Climate Experiment (GRACE)	Terra and Aqua	Aqua
Sensors	SuperSTAR Accelerometer Star Camera Assembly K-Band Ranging System	Clouds and the Earth's Radiant Energy System (CERES)	Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E)
Data sets	GRACE Monthly Land Water Mass Grids (CSR)	SYN1deg_Ed3a	Daily Global Land Surface Parameters Derived from AMSR-E
Resolution	1 degree	1 degree	25 kilometer
Parameters	Terrestrial water storage anomalies	Radiative flux	Canopy microwave transmittance
DAACs	NASA Physical Oceanography DAAC (PO.DAAC)	NASA Atmospheric Science Data Center DAAC (ASDC DAAC)	NASA National Snow and Ice Data Center DAAC (NSIDC DAAC)

References

Jones, L. A. and J. S. Kimball. 2010, updated 2012. Daily Global Land Surface Parameters Derived from AMSR-E. Boulder, CO, USA: NASA National Snow and Ice Data Center Distributed Active Archive Center.

NASA Atmospheric Science Data Center DAAC (ASDC DAAC). 2003-2012. Clouds and the Earth's Radiant Energy System (CERES) SYN1 deg_Ed3a. Hampton, VA, USA.

NASA Goddard Earth Sciences DAAC (GES DAAC). 1998-2012. Tropical Rainfall Measuring Mission Multi-Satellite Precipitation Analysis. Greenbelt, MD, USA.

NASA Land Processes Distributed Active Archive Center (LP DAAC). 2000-2012, monthly. MODIS Vegetation Indices MOD13C2. USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD, USA, doi:10.5067/MODIS/MOD13C2.006.

NASA Land Processes Distributed Active Archive Center (LP DAAC). 2003-2012, monthly. MODIS Land Surface Temperature and Emissivity MYD11C3. USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD, USA, doi:10.5067/MODIS/MYD11C3.006.

NASA Land Processes Distributed Active Archive Center (LP DAAC). 2001-2012, yearly. MODIS Land Cover Type MCD12C1. USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD, USA, doi:10.5067/MODIS/MCD12C1.006.

About the scientists

Philippe Ciais is the head of the Atmospheric Composition Department at the Laboratoire des Sciences du Climat et de l'Environnement in France. His research focuses on the global carbon cycle. The Commissariat à l'Energie Atomique supported his research. Read more at http://goo.gl/bnGNs7. (Photograph courtesy P. Ciais)

Liming Zhou is an associate professor at the Department of Atmospheric and Environmental Sciences at University at Albany, State University of New York. His research interests include land-surface remote sensing, land-climate interactions, land-surface modeling, and land-human-climate interactions. NASA and the National Oceanic and Atmospheric Administration supported his research. Read more at http://goo.gl/KLXfRf. (Photograph courtesy L. Zhou)

NASA MODIS Level 1 and Atmosphere Archive and Distribution System (MODAPS DAAC). 2002-2012, monthly. MODIS/Gridded Atmospheric Product MOD08_M3. Greenbelt, MD, USA, doi:10.5067/MODIS/MOD08_M3.006.

Swenson, S. C. 2012. GRACE Monthly Land Water Mass Grids NETCDF Release 5.0. Ver. 5.0. PO.DAAC, CA, USA. http://dx.doi.org/10.5067/TELND-NC005.

Zhou, L., Y. Tian, R. B. Myneni, P. Ciais, S. Saatchi, Y. Y. Liu, S. Piao, H. Chen, E. F. Vermote, C. Songe, and T. Hwang. 2014. Widespread decline of Congo rainforest greenness in the past decade. *Nature* 509: 86-90, doi:10.1038/nature13265.

For more information

NASA Land Processes Distributed Active Archive Center (LP DAAC)
http://lpdaac.usgs.gov

NASA MODIS Level 1 and Atmosphere Archive and Distribution System DAAC (MODAPS DAAC)
http://laadsweb.nascom.nasa.gov

Missing heat

> "People are looking for a simple explanation of where the heat is going."
>
> Richard Allan
> University of Reading

by Laura Naranjo

When the mercury thermometer was invented in 1714, it took the scientific world by storm. On his transatlantic crossing in the year 1724, Benjamin Franklin recorded water temperatures by periodically dipping a thermometer into the ocean. By 1850, weather stations across the globe had gleaned a record of air temperatures over land. For the first time, scientists could track Earth's temperature. And over time, it became clear that temperature was rising.

But after rapid warming in the 1980s and 1990s, the rate seemed to slow. Continued high continental temperatures were offset by curiously cool ocean surfaces. Yet most scientific evidence, and the inexorable increases in heat trapping

Moist air coming off the ocean produces clouds along the Big Sur coast south of Monterey, California. (Courtesy R. Schwemmer, National Oceanic and Atmospheric Administration)

greenhouse gases, indicated global temperatures should be climbing at a greater rate. This missing heat had to go somewhere—if not in the surface layers, where?

Accounting for heat

Richard Allan, a professor of climate science at the University of Reading, contends the heat is not really missing. "People are looking for a simple explanation of where the heat is going," Allan said. "But I think it's a combination of factors." Understanding these factors required tallying Earth's entire energy balance: how much sunlight enters Earth's atmosphere, how much of this energy is reflected and emitted back out to space, and where energy—in the form of heat—is being stored in Earth's climate system.

This radiation exchange is best measured at the top of the atmosphere, where sunlight enters Earth's climate system, and where orbiting satellites can act like a proxy thermometer. Allan's team used data from the Clouds and the Earth's Radiant Energy System (CERES) satellite instrument, launched in 2000, plus data from the Earth Radiation Budget Satellite (ERBS), which extended the record back to 1984. These data, obtained from the NASA Atmospheric Science Data Center Distributed Active Archive Center, captured incoming and reflected sunlight and emitted infrared radiation over the recent period in which the rate of global surface warming has appeared to wane. "We found the heating rate, based on this long satellite record, hadn't declined," Allan said. "In fact, if anything, the heating rates have become greater in the 2000s than in the period prior to it."

If the surface warming has slowed, then where is this extra accumulating heat going? Air, land, and water absorb and release heat at different rates, and on vastly different time scales. For instance, on a summer walk along a sunny beach, the sand and air will feel quite warm, but the ocean will not. Large bodies of water possess more thermal inertia than land or air, meaning oceans will absorb heat more slowly, and will be slower to release that heat even when land or air temperatures cool. Complicating matters, different ocean layers store and release heat at different rates. Water temperatures near the ocean surface tend to be more variable, because there is a constant heat exchange with the air circulating above. Deeper ocean layers, however, exchange heat more slowly than surface layers and release that stored heat on much longer time scales. So to find the missing heat, researchers dove into the oceans.
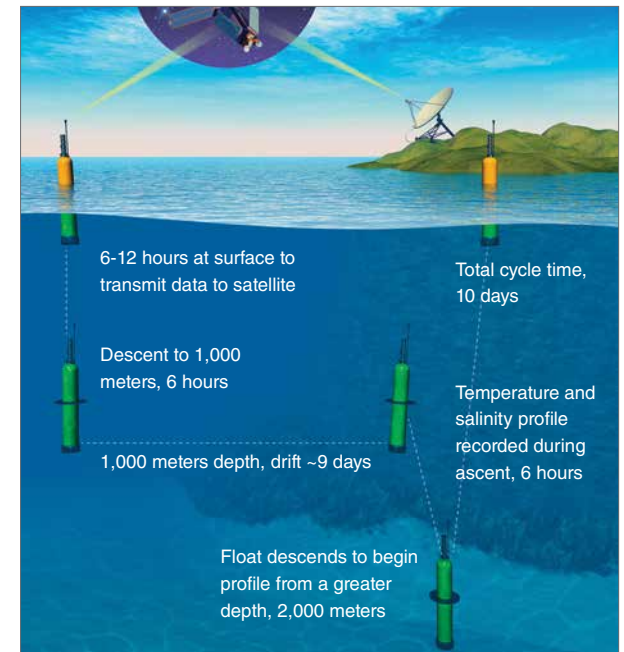
Answers in the ocean

Scientists still measure ocean temperature by submerging instruments, but now they tap a global network of thousands of submersible floats. Deployed by the Argo project, these meter-long tubes contain temperature, salinity, and pressure sensors. They are designed to dive, drift, and then surface to relay data on ten-day cycles. The project began in 2000 with floats diving to 1,000 meters (0.62 miles), and since 2005, floats have been diving to 2,000 meters (1.24 miles). Argo floats permit researchers to observe deeper layers of the ocean that absorb heat over longer time scales. Once Allan and his colleagues had data from both the floats and the satellite instruments, they could calculate the energy imbalance.
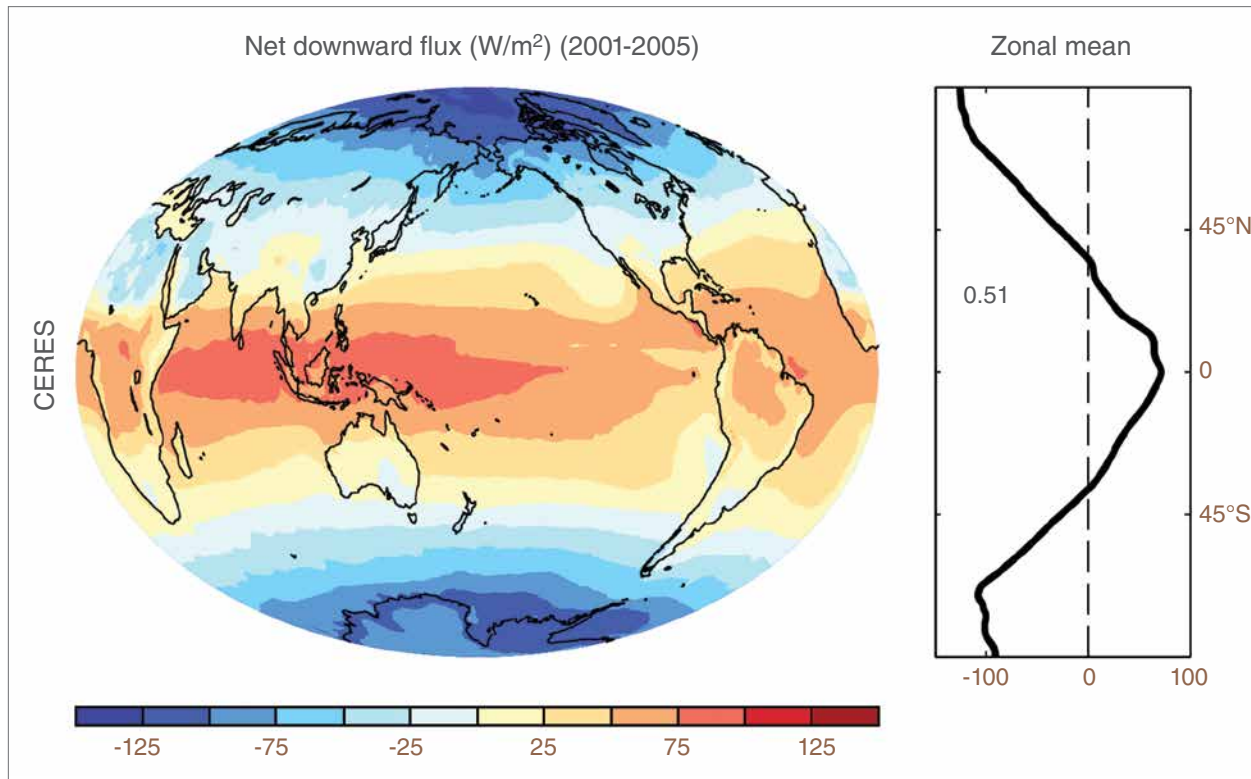
They found that the "missing" heat had actually been continuing to build up over the satellite record and the only place it could be was lurking beneath the ocean surface. Heat not exchanged

Researchers deploy an Argo float, a submersible instrument that records ocean temperatures and other data up to 2,000 meters (1.24 miles) deep. (Courtesy Argo Program)

6-12 hours at surface to transmit data to satellite

Total cycle time, 10 days

Descent to 1,000 meters, 6 hours

1,000 meters depth, drift ~9 days

Temperature and salinity profile recorded during ascent, 6 hours

Float descends to begin profile from a greater depth, 2,000 meters

This illustration shows how Argo floats, dive, drift, and then surface to transmit ocean temperatures. (Courtesy Argo Program/Scripps Institution of Oceanography)

Net downward flux (W/m²) (2001-2005)   Zonal mean

CERES

0.51

45°N

0

45°S

-100   0   100

-125   -75   -25   25   75   125

This image shows net downward radiation flux at the top of Earth's atmosphere in watts per square meter. Blues indicate regions losing heat; oranges and reds indicate where heat is building up. Averaged over the globe for the 2001-2005 period, 0.51 watts per square meter of energy are accumulating, which is causing the planet to warm. Data are from the Clouds and Earth's Radiant Energy System (CERES), which helps scientists understand Earth's heat budget. (Courtesy R. P. Allan)

with the atmosphere at the ocean surface can eventually circulate into deeper layers. "In some decades this penetration of heat to deeper layers becomes more efficient, and simulations and observations suggest that this was the case in the 2000s," Allan said. "This explains how you can have a slowing in the surface warming yet heat is continuing to accumulate at a greater rate."

Ocean temperature data were critical to gauge the imbalance, but over the long term, scientists need both the Argo and satellite records. "While

the ocean data are the most important in determining how much the Earth is heating up, the ERBS and CERES data can accurately track changes in this heating rate and measure the shorter term fluctuations much better than the ocean data alone," Allan said.

Modeling the energy budget

But the scientists wondered whether simulations used to make projections of future climate change could capture the changes in Earth's energy imbalance found in the Argo and satellite

data. They compared their findings with a spectrum of climate models that simulated Earth's recent conditions. "No one model is perfect," said atmospheric scientist Norman Loeb, one of Allan's colleagues. "So there's an interest in looking at the ensemble of different climate models to get a sense of how they are performing relative to observations."

The models are designed to simulate the slow but chaotic variations of our vast oceans. Allan said, "If you're watching a river, you'd see all these chaotic fluctuations in the river from one moment to the next. With the ocean, things work on much slower time scales, so you get the same sorts of fluctuations, but on a decade-to-decade range." For instance, a series of strong La Niñas since 2000 kept the ocean surface cool, which weakened the normal rate of heat loss from the ocean surface to the atmosphere above and led to more heat penetrating to deeper ocean layers.

"The models are trying to represent the true variability," Loeb said. "They're trying to capture the changes in El Niños and La Niñas and how they impact the energy imbalance at the top of the atmosphere." These changes include natural variability, but also include factors that force imbalances in Earth's climate system, such as volcanic eruptions or greenhouse gases. "For example," said Loeb, "the biggest forcing in the record is from the Mount Pinatubo eruption." The 1991 eruption in the Philippines injected massive amounts of ash and particles into the atmosphere, dampening global temperatures and altering Earth's climate for several years.

Imbalance and variability

The researchers concluded that the recent slowing in global surface warming is part of natural

climate fluctuations. But the energy budget is still out of balance, which translates into heat no matter where it accumulates. Loeb said, "You could think of the oceans as causing a thermal lag on the system, and over time, the system will tend to warm up to try and restore the equilibrium. But it takes place over a long period of time because of the ocean's ability to store heat." Earth's climate system perpetually tries to restore the balance, and this absorbed heat will eventually make its way back into the atmosphere.

Over the long term, additional heat leads to sea level rise. "When the oceans warm, they expand. And that raises sea level," Allan said. "On the other hand, when land warms, and glaciers and ice sheets melt, that adds extra water to the ocean, which also raises sea level." It takes hundreds of years for heat to penetrate to the depths of the ocean and for giant ice sheets to melt. "That's why sea level rise is a multi-century problem," said Allan.

Heat can travel through the oceans and influence climate differently in different parts of the world. For instance, research involving NASA indicates that heat accumulating beneath the Pacific Ocean surface may have traveled to the Indian Ocean. Scientists are still trying to understand which climate patterns are part of natural variability, and which are being changed by human activity. "We're only actually sampling a few of the bumps and dips of decadal variations," Allan said. "Continued tracking of Earth's energy balance is crucial for gauging how future warming will progress as human activities continue to pump greenhouse gases into the atmosphere." And this has major implications for the consequent impacts on human societies and the ecosystems upon which they depend.

About the remote sensing data

Satellites	Terra and Aqua	Earth Radiation Budget Satellite (ERBS)
Sensors	Clouds and the Earth's Radiant Energy System (CERES)	Wide Field-of-View (WFOV) Nonscanner
Data sets	CERES EBAF Ed2.7	ERBS WFOV 3.1
Resolution	1 x 1 degree	10 x 10 degree
Parameters	Radiance	Radiance
DAACs	NASA Atmospheric Science Data Center Distributed Active Archive Center (ASDC DAAC)	NASA ASDC DAAC

About the scientists

Richard P. Allan is a professor of climate science at the University of Reading. He studies the global water cycle, and how fluctuations in clouds, water vapor, and rainfall influence Earth's climate system. The Natural Environment Research Council DEEP-C grant, the National Centre for Atmospheric Science, and the National Centre for Earth Observation supported his research. Read more at http://goo.gl/Dcocwp. (Photograph courtesy R. P. Allan)

Norman Loeb is a physical scientist at the NASA Langley Research Center and principal investigator for NASA's Clouds and the Earth's Radiant Energy System (CERES) project. He uses remote sensing to study Earth's radiation budget. NASA supported his research. Read more at http://goo.gl/eJPXzW. (Photograph courtesy K. Lorentz/NASA)

To access this article online, please visit https://earthdata.nasa .gov/sensing-our-planet/missing-heat.

References

Allan, R. P., C. Liu, N. G. Loeb, M. D. Palmer, M. Roberts, D. Smith, and P.-L. Vidale. 2014. Changes in global net radiative imbalance 1985-2012. *Geophysical Research Letters* 41: 5,588–5,597, doi:10.1002/2014GL060962.

NASA Atmospheric Science Data Center DAAC (ASDC DAAC). CERES Energy Balance and Filled Top of the Atmosphere (EBAF-TOA) Ed2.7, Hampton, VA, USA. http://ceres.larc.nasa.gov/products.php ?product=EBAF-TOA.

NASA Atmospheric Science Data Center DAAC (ASDC DAAC). Earth Radiation Budget Satellite Wide Field-of-View (ERBS WFOV) 3.1, Hampton, VA, USA. https://eosweb.larc.nasa.gov/project/erbe/erbe_table.

For more information

NASA Atmospheric Science Data Center Distributed Active Archive Center (ASDC DAAC) https://eosweb.larc.nasa.gov

Clouds and Earth's Radiant Energy System (CERES) http://ceres.larc.nasa.gov/index.php

Earth Radiation Budget Satellite (ERBS) Nonscanner Wide Field-of-View (WFOV) instrument http://science.larc.nasa.gov/erbe/erbenonscan.html

Tracing the Tehuano

"The challenge was to develop code that can do what the human eye can do."

Deborah K. Smith
Remote Sensing Systems

by Natasha Vizcarra

Before the sun rises, members of the Icot people set out fishing kites in Mexico's Gulf of Tehuantepec (teh-wahn-teh-pek). Offshore, five-foot nylon kites rise quickly, anchored by buckets of stones and tethered to nets sousing in freaky, ten-foot waves. These winter waters turn violent with the squally Tehuano wind. It can blow without warning on a clear day, packing gale- or hurricane-force winds. The kites fly all night as strong winds upwell colder, nutrient-rich water. Icot fishermen return the next day to a bounty of fish, more than 600 pounds without setting foot in the turbulent waters.

Scientists want to decode the Tehuano's unpredictable and violent nature to keep mariners safe. But they are also curious about the wind's relationship with other processes, big and small. Does the Tehuano cause the upwelling, for example, or is it caused by something else? Is it just a local weather event, or does it contribute to that complicated, global climate soup? More importantly, can the Tehuano be predicted?

Deborah K. Smith, a geographer and remote sensing expert, is part of a team eager to build a climatology for the Tehuano: wind and sea surface temperature measurements of the event spanning many years. Climatologies power global climate

Canoes are moored at Playa de San Mateo del Mar on the Isthmus of Tehuantepec in Oaxaca, Mexico. (Courtesy L. Brehmer and E. Flores-Guevara)

models and weather forecasts. They average weather statistics accumulated over many years. "We faced a massive amount of data," Smith said. To succeed, a computer algorithm would need to know when a Tehuano was present.

The gap

Smith and her colleagues have never been to the Gulf of Tehuantepec. They worked exclusively with remote sensing data, exchanging e-mails and conducting phone conferences from Santa Rosa, California with Smith's colleagues at the University of Alabama in Huntsville (UAH). Unfortunately, weather instruments in the study area are scarce. "Over land there are plenty of wind anemometers. In the ocean, there are very few," Smith said. "The only place you would put an anemometer is on a ship or on a buoy, and we only have so many of those out there."

For Ken Keiser, who leads the algorithm development team, and primary developer Xiang Li, both at UAH, the biggest challenge was getting to know the Tehuano itself. "I needed to fully understand the physical properties of the Tehuano and the ocean upwelling to write the algorithm that identifies these features," Keiser said.

The researchers traced the Tehuano's genesis in North America, where cold outbreaks over the Great Plains trigger air pressure differences that flow southward to eastern Mexico and the Bay of Campeche. The winds funnel through the Chivela Pass, a narrow gap in the Sierra Madre Mountains. This forces the winds to accelerate, much like air hisses out of a tire leak. The winds emerge as a wind jet with speeds in excess of 20 meters per second (45 miles per hour). For this reason, scientists call the Tehuano a coastal gap wind jet, or simply gap wind.

The Tehuano can extend hundreds of kilometers out into the Gulf of Tehuantepec and beyond into the Pacific Ocean. On the water, it causes a big drop in sea surface temperature. "The wind pushes the surface water away," Smith said. "That causes cold water to come up and create really good fishing areas." Seasoned boaters know it is the Tehuano when waves crash away from the shore instead of toward it.

Smith and her colleagues looked at ocean surface wind and sea surface temperature data from the NASA Physical Oceanography Distributed Active Archive Center to extract all the Tehuano events in the data series. But it would have taken them years to sort the satellite images manually. "The human eye can pick out the Tehuano immediately," Smith said. "That's difficult to do in an automated fashion. The challenge was to develop code that can do what the human eye can do."

A tongue of wind

"The Tehuano comes from the land out to sea and it looks a lot like a channel of very high winds with much weaker winds on either side," Smith said. The wind vector image of the Tehuano is peppered with tiny arrows that indicate wind direction, and the waters off eastern Mexico, Texas, and Florida are full of arrows pointing south. Warm colors indicate high wind speed, and it is orange and yellow all over these waters. Then, just south of the Isthmus of Tehuantepec where North America ends and Central America begins, arrows spew southward and westward, over intense red and fuchsia shades. It looks like southern Mexico grew a tongue and is licking the Pacific Ocean.

The UAH team developed an algorithm to recognize this, and then sent Smith a test batch


A villager stands alongside a fishing kite and nets. Using kites to fish during a Tehuano is a way of life for the people of San Mateo and Santa Maria del Mar in the Isthmus of Tehuantepec, Mexico. (Courtesy C. Ornelas)

of detected Tehuano events. "I would compare their list to my own visual observation," Smith said. "We iterated back and forth quite a bit." The algorithm's goal was to identify the Tehuano's extent, when it started and when it ended. It also recorded wind statistics, like maximum speed, mean and standard deviation of the wind speeds and wind directions, and mean latitude and longitude of the detected region.

"The hard part wasn't identifying the strong days," Smith said. "It was the weaker days. What was the start or the end? When was it weakening or strengthening? How do you identify those in a satellite image?"

To solve this, the team labored over pixel by ambiguous pixel. "Sometimes you see a red pixel
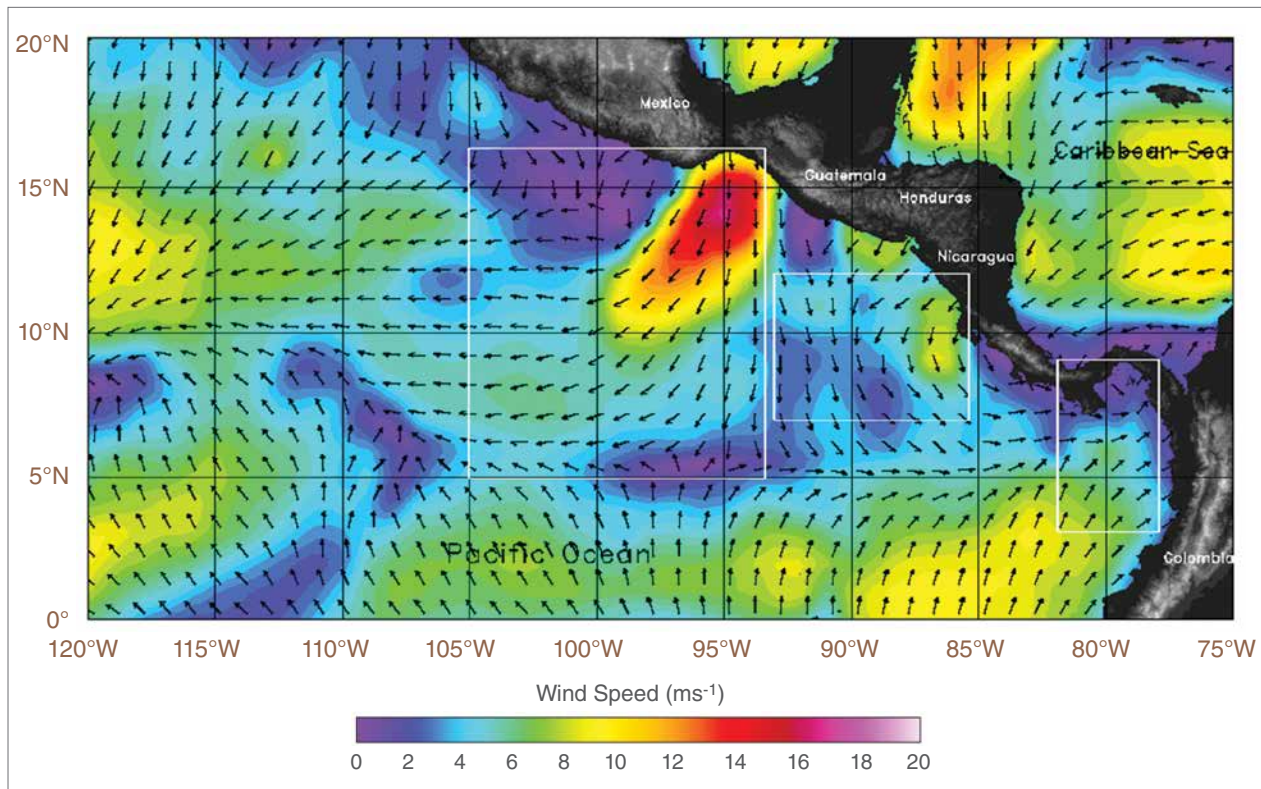
This image shows wind speed, in meters per second, and direction data over Central America for December 17, 2007 at 0600 Zulu time showing characteristics of a Tehuano wind. Arrows indicate wind direction, warm colors (yellow to magenta) indicate high wind speed and cooler colors (purple to green) indicate lower wind speed. The white squares mark the boundaries of three gap wind climatologies available in the Regional Air-Sea Interactions (RASI) data set: Tehuantepec, Papagayo, and Panama. (Courtesy NASA Global Hydrology Resource Center [GHRC])

and then a yellow again which means slower wind speed," Smith said. "That tricks the algorithm into thinking that it's the edge of the gap wind." It could be something natural slowing the wind, or it could be a satellite issue.

It took three years of back and forth work between the colleagues, and when they finished they had a thirteen-year climatology for the Tehuano and two smaller gap winds in the nearby gulfs of Papagayo and Panama. The climatologies, called Regional Air-Sea Interac-tions (RASI), span 1998 to 2011 and are archived at and distributed by the NASA Global Hydrol-ogy Resource Center Distributed Active Archive Center. The center also hosts a RASI exploration tool, which allows users to locate gap winds and ocean upwellings, and to visualize, plot and download the data.

The name of the wind

It is not just Central America that benefits from this algorithm. Other parts of the world could adapt it to build climatologies for their gap winds. The Mistral, for example, funnels through the valley of Rhone in southern France into the Mediterranean Sea. In Switzerland, there is the Jochwinde. In Greenland, there is the tip jet at the island's southern end.

Mariners and pilots turn to global models for information about when these gap winds might happen. Smith said global models just do not have enough resolution for that. "The physics for these models are designed for larger-scale things, not these small scale regional features," Smith said. Global models have a one degree resolu-tion. The RASI climatology zooms into a quarter degree—just right for regional forecasts.

Emily Foshee, a graduate student at UAH, is now using the climatologies to develop a method to forecast the Tehuano, Papagayo, and Panama gap winds. The climatologies also promise to shed light on bigger puzzles. Keiser said, "The same tech we use to identify these features can be applied to hurricanes. The upwelling that gap winds cause can influence how hurricanes strengthen." It might take some finagling, but the algorithm might help global models improve hurricane intensification forecasts.

To Smith, being able to study patterns in these climatologies is a powerful tool. "That's where the RASI comes in. You can see the patterns," she said. "Are they changing with global climate change and if so, have they started or ended earlier in the season? These questions can be explored because we now have this information. That's very exciting."

To access this article online, please visit https://earthdata.nasa .gov/sensing-our-planet/tracing-the-tehuano.

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References

Li, X. and D. Smith. 2014. Regional Air-Sea Interaction (RASI) Gap Wind and Coastal Upwelling Events Climatology [indicate sites used]. Data sets available online [ftp://ghrc.nsstc.nasa.gov/pub/rasi/] from the NASA EOSDIS Global Hydrology Resource Center Distributed Active Archive Center Huntsville, AL, U.S.A. doi: http://dx.doi.org/10.5067/MEASURES/RASI/DATA404.

NASA/GSFC/NOAA. 2009. Cross-Calibrated Multi-Platform Ocean Surface Wind Vector L3.0 First-Look Analyses. Ver. 1. PO.DAAC, CA, USA. http://dx.doi.org/10.5067/CCF30-01XXX.

Ornelas, C. 2008. Adrift in el Istmo: a Kite Journey to Juchitán. *Discourse: from the end of the line* 1(3): 23–30. http://www.drachen.org/sites/default/files/pdf/Discourse%20Issue%203.pdf.

Remote Sensing Systems. 2011. GHRSST Level 2P Gridded Global Subskin Sea Surface Temperature from WindSat polarimetric radiometer on the Coriolis satellite. Ver. 7.0. PO.DAAC, CA, USA. http://dx.doi.org/10.5067/GHWST-2GR01.

Remote Sensing Systems. 2011. AMSR-E Level 3 Sea Surface Temperature for Climate Model Comparison. Ver. 1. PO.DAAC, CA, USA.

Remote Sensing Systems. 2004. GHRSST Level 2P Global Subskin Sea Surface Temperature from the Tropical Rainfall Mapping Mission (TRMM) Microwave Imager (TMI). Ver. 4.0. PO.DAAC, CA, USA. http://dx.doi.org/10.5067/GHTMI-2PR01.

About the scientists

Emily Foshee is a graduate student in atmospheric sciences at the University of Alabama in Huntsville. Her research focuses on mesoscale meteorology and understanding mountain gap winds. The NASA Earth and Space Science Fellowship supported her research. (Photograph courtesy University of Alabama in Huntsville)

Ken Keiser is a research scientist with the Information Technology and Systems Center at the University of Alabama in Huntsville. His research focuses on applied information technology solutions for Earth science data and information problems. The NASA MEaSUREs program supported his research. (Photograph courtesy K. Keiser)

Deborah K. Smith is a research scientist at Remote Sensing Systems. Her research focuses on the analysis of tropical cyclone winds using scatterometer and radiometer data, the detection and characterization of regional winds, and developing automated detection for gap winds and associated cold water upwelling. The NASA MEaSUREs program supported her research. Read more at http://goo.gl/9cjHIJ. (Photograph courtesy Remote Sensing Systems)

Smith, D. K., X. Li, K. Keiser, and S. Flynn. 2014. Regional Air-Sea Interactions (RASI) climatology for Central America coastal gap wind and upwelling events. Paper presented at the OCEANS 2014 Marine Technology Society/Institute of Electrical and Electronics Engineers Conference, St. John, Newfoundland. doi: 10.1109/OCEANS.2014.7003127.

For more information

NASA Global Hydrology Resource Center Distributed Active Archive Center (GHRC DAAC)
https://ghrc.nsstc.nasa.gov
NASA Physical Oceanography DAAC (PO.DAAC)
http://podaac.jpl.nasa.gov
Regional Air-Sea Interactions
https://ghrc.nsstc.nasa.gov/rasi/main.php

A submarine retreat

"It's a game changer for sea level."

Eric Rignot
University of California Irvine

by Jane Beitler

On the world's largest island sits the second largest body of ice. In summer, the ice heads for the ocean as the sun's warmth melts the Greenland Ice Sheet surface in turquoise-blue ponds. Meltwater percolates through pocks and out into rushing streams. In the green fjords ringing the coast, slabs of ice plunge off glacier fronts, pushed out by the slow flow of glaciers that serve as major outlets for ice discharge.

A warmer planet is tipping the balance between ice accumulation and loss in Greenland. Showy, fast-moving Jakobshavn Glacier was filmed spectacularly calving 1.8 cubic miles of ice in 2012, and is thought to have calved the iceberg that sunk the Titanic. Less showy glaciers like Upernavik Glacier may be hiding secrets about the ice sheet's future. Researchers such as ice sheet modeler Mathieu Morlighem are peering beneath glaciers to the bedrock below and overturning assumptions about how the Greenland Ice Sheet may respond to a warmer climate.

A glacier's journey

More than 100,000 years old and up to two miles thick, the ice sheet has been waning in

This view along Steensby Glacier in northern Greenland was seen during an Operation IceBridge survey flight on April 26, 2013. (Courtesy NASA/M. Studinger)

recent decades. It contains enough ice to raise sea levels twenty-four feet, if all of it melted.

If warmth is the accelerator pedal, topography can be the brakes. Greenland has more than 200 valleys and canyons, which channel glacier ice from the island's high interior to its coasts. Glaciers move slowly in twisting valleys, and faster in straight valleys. However, the glaciers' ice mostly hides the terrain that influences this flow.

When the base of the glacier, or its grounding point, is below sea level when it reaches the coast, the ice can contact a layer of warm Atlantic water a thousand feet below the surface, speeding ice discharge. But how many of these valley floors are below the ocean surface, and for what distance upstream? The data at hand portrayed Greenland's valleys as shallow.

"Lots of people used to say that the Greenland Ice Sheet is not so vulnerable to climate change, because once the glaciers retreat inland about ten kilometers [six miles], they will not be connected to the ocean, and so the melting we see today will stop," Morlighem said. There, the elevation of the valley floor would rise above sea level and stop the ocean from following a glacier up the valley. However, researchers knew that something was amiss when ice sheet models were not able to simulate current rates of melting and ice sheet thinning.

Stop kriging the bed

Morlighem builds ice sheet models, which use data to simulate how the ice sheet will respond to environmental change. He admits that he is standing on the shoulders of Jonathan Bamber at University of Bristol. Since the 1990s, Bamber has used airborne radar to study the geometry of

Greenland's glacier valleys. In 2013, Bamber's team compiled thousands of miles of ice-penetrating radar flightlines collected over the ice sheet as part of NASA Operation IceBridge. They produced a bedrock elevation data set for Greenland, extending out to the continental shelves.

As they compiled the data, they discovered a huge canyon running from the central region of the island northward to the fjord of Petermann Glacier and the Arctic Ocean. Dubbed "Greenland's Grand Canyon," it is more than 750 kilometers long (466 miles), up to 800 meters deep (2,600 feet), and 10 kilometers wide (6 miles), making it the longest canyon discovered on Earth. They think the canyon is a major channel for flushing ice and meltwater off the island. Without canyons like this, meltwater might pool under the ice sheet and form subglacial lakes, as are found under the ice sheet on Antarctica. Greenland has no lakes below its ice sheet.

Still, important questions hung in the air, and radar data were too sparse to answer them. "Originally the bed topography map was derived from data collected along flight lines from Operation IceBridge. These were point measurements. In between we have nothing," Morlighem said. "People used kriging, a kind of clever averaging where you look at neighboring data." With too-sparse observations, however, kriging tended to smooth out and eliminate directional land features, like valleys and troughs, so the models could not accurately simulate ice thickness and velocity.

"So the previous maps we were using were not good enough to run the models at a higher resolution," Morlighem said. In addition, crevasses, rough terrain, and pockets of liquid water all


The calving front of Petermann Glacier in northern Greenland is seen from the NASA P-3B aircraft during Operation IceBridge. In July 2012, an iceberg twice the size of Manhattan broke off of Petermann Glacier and began to float away in the ocean. After this calving event, the line where the iceberg broke away became the glacier's new front edge, or calving front, effectively moving it several kilometers upstream. Several valley glaciers are now flowing into the fjord, covered by sea ice. (Courtesy NASA/M. Studinger)

confuse the radar, foiling attempts to interpolate the sparse measurements. "We had to devise a new method," he said.

A zero sum game

Eric Rignot at University of California Irvine, who worked on the study, said, "We've struggled with the problem of not having glacier thickness for a number of years. I encouraged Mathieu to go with a more modern, powerful version of a mass conservation method of calculating thickness." Mass conservation assumes that mass is never lost, but accounts for inputs and outputs, such as snow accumulation, ice velocity, and melt. To get the ice volume, you need to know how thick it is, and to calculate thickness you need the elevation of the ice surface and of the ice bottom, on the rock. The bottom elevation
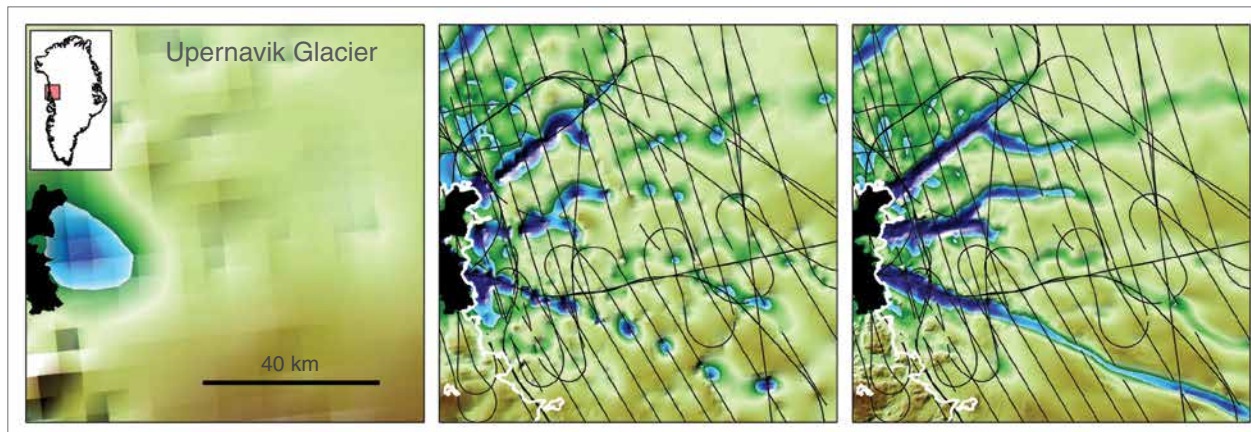
These images show the progress of methods for studying the bedrock elevation beneath the Greenland Ice Sheet. The first column shows bed topography derived from airborne radar in 2001. The second column shows improved results using ice-penetrating radar flown during NASA Operation IceBridge (OIB). The third column shows bed topography from applying a mass conservation technique. This technique produces smoother data along flight lines, and preserves the elongated features of the valleys. It also works with very sparse measurements. Blues indicate bed elevations that are below sea level. The black lines on the images in the second and third columns indicate the OIB flight lines. The data also reveal that the bed topography is below sea level all the way to the coast. (Courtesy M. Morlighem et al.)

would also tell how far the ocean would be able to reach up the glacier stream as it retreated. Some of this detail was lacking.

Morlighem's team used the mass conservation approach to back into the bed elevation detail. They combined the sparse airborne data with high-resolution ice motion data from satellite Interferometric Synthetic Aperture Radar (InSAR). They could then calculate ice thickness more accurately by accounting for ice velocity. Bed topography could be deduced by subtracting ice thickness from a digital elevation model of the ice surface.

Their results show the widespread presence of well-eroded, deep bed troughs along the edges of the ice sheet that are generally grounded below sea level, with fast-flowing ice. They extend more than 100 kilometers (62 miles) inland, not the 10 kilometers (6.2 miles) that had been thought.

The full extent of some of these bed troughs had never been detected by previous radar sounders.

Bamber said, "The work that Mathieu and that group are doing is fantastic. It tackles one of the problems that we knew existed. Mathieu is working on the problems around the ice sheet's edge. It wouldn't work in the ice sheet's interior and where you don't have this clear directional flow."

Deeply incised

Fast-moving Greenland glaciers such as Jakobshavn Glacier remain important channels for ice discharge. Yet this new view of deep, submarine valleys sheds a different light on the long-term decline of the ice sheet.

"In many places we thought that the bed was raised above sea level but it was below sea level," Morlighem said. For the first time, for example,

they could see that the bed of the three main branches of Upernavik Glacier in West Greenland runs below sea level for more than 80 to 140 kilometers (50 to 87 miles) inland. Up north, Humboldt Glacier's submarine bed runs 140 kilometers (87 miles) inland. Morlighem said, "We now know that the melting of Greenland is not going to stop in a decade or so. It will keep melting. As the ice retreats, it will still be in contact with the ocean because it will follow it inland."

The original radar data and the new bedrock data set are both archived at the NASA National Snow and Ice Data Center Distributed Active Archive Center for further study. "All these efforts will eventually lead to modern data sets for the ice sheets and provide what modelers need to project ice sheets in a warming world. These are critical and timely results," Rignot said. "The submarine valleys make the glaciers more susceptible to rapid, prolonged retreat. It's a game changer for sea level. Sea level rise from Greenland will be higher than models currently project."

To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/a-submarine-retreat.

References

ALOS PALSAR data 2008-2009 (JAXA, METI). Retrieved from the Alaska Satellite Facility SAR DAAC, https://www.asf.alaska.edu.

Bamber, J. L., J. A. Griggs, R. T. W. L. Hurkmans, J. A. Dowdeswell, S. P. Gogineni, I. Howat, J. Mouginot, J. Paden, S. Palmer, E. Rignot, and D. Steinhage. 2013. A new bed elevation dataset for Greenland. *The Cryosphere* 7: 499–510, doi:10.5194/tc-7-499-2013.

Bamber, J. L., M. J. Siegert, J. A. Griggs, S. J. Marshall, and G. Spada. 2013. Paleofluvial mega-canyon beneath the central Greenland Ice Sheet. *Science* 341(6149): 997–999, doi:10.1126/science.1239794.

About the data

		Canadian Space Agency RADARSAT-1	Japan Aerospace Exploration Agency Advanced Land Observing Satellite (ALOS)
Satellites		Canadian Space Agency RADARSAT-1	Japan Aerospace Exploration Agency Advanced Land Observing Satellite (ALOS)
Platforms	Douglas DC-8, Lockheed P-3B Orion		
Sensors	Multichannel Coherent Radar Depth Sounder (MCoRDS)	Synthetic Aperture Radar (SAR)	Phased Array type L-Band Synthetic Aperture Radar (PALSAR)
Data sets	IceBridge MCoRDS L2 Ice Thickness	RADARSAT-1 Level 0 Data	ALOS PALSAR Level 1.0 Data
Resolution	17.8 to 965 meters	8 to 100 meters	100 to 250 meters
Parameters	Ice sheet elevation Ice sheet thickness	Reflectance	Reflectance
DAACs	NASA National Snow and Ice Data Center Distributed Active Archive Center DAAC (NSIDC DAAC)	NASA Alaska Satellite Facility Synthetic Aperture Radar DAAC (ASF SAR DAAC)	NASA ASF SAR DAAC

The bedrock data set produced by this study, IceBridge BedMachine Greenland, Version 2, is also archived at the NSIDC DAAC.

Leuschen, C., P. Gogineni, F. Rodriguez-Morales, J. Paden, and C. Allen. 2010, updated 2015. IceBridge MCoRDS L2 Ice Thickness. Boulder, CO, USA: NASA DAAC at the National Snow and Ice Data Center. http://dx.doi .org/10.5067/GDQ0CUCVTE2Q.

Morlighem, M., E. Rignot, J. Mouginot, H. Seroussi, and E. Larour. 2014. Deeply incised submarine glacial valleys beneath the Greenland ice sheet. *Nature Geoscience* 7: 418–422, doi:10.1038/ngeo2167.

Morlighem, M., E. Rignot, J. Mouginot, H. Seroussi, and E. Larour. 2015. IceBridge BedMachine Greenland. Version 2. Boulder, CO, USA: NASA National Snow and Ice Data Center Distributed Active Archive Center. http://dx.doi.org/10.5067/AD7B0HQNSJ29.

RADARSAT-1 data 2008-2009 (CSA). Retrieved from the Alaska Satellite Facility SAR DAAC, https://www .asf.alaska.edu.

For more information

NASA Alaska Satellite Facility Synthetic Aperture Radar Distributed Active Archive Center (ASF SAR DAAC) http://www.asf.alaska.edu

NASA National Snow and Ice Data Center DAAC http://nsidc.org/daac

NASA Operation IceBridge http://www.nasa.gov/mission_pages/icebridge

About the scientists

Jonathan Bamber is a professor of physical geography and director of the Bristol Glaciology Centre at Bristol University. His research interests include satellite and airborne remote sensing data of the polar regions, focusing mainly on Greenland and Antarctica. Since 2007, he has been editor in chief of the journal *The Cryosphere*. NASA supported his research. Read more at http://goo.gl/VTufm1. (Photograph courtesy J. Bamber)

Mathieu Morlighem is an assistant professor of Earth system science at University of California Irvine. His research interests include better understanding of and explaining ongoing changes in the cryosphere, as well as reducing uncertainties in the ice sheet contribution to sea level rise using numerical modeling. NASA supported his research. Read more at http://goo.gl/puaqI3. (Photograph courtesy University of California Irvine)

Eric Rignot is a professor of Earth system science at University of California Irvine and a senior research scientist at the NASA Jet Propulsion Laboratory. His research interests include glaciology, climate change, radar remote sensing, ice sheet modeling, interferometry, radio echo sounding, and ice-ocean interactions. NASA supported his research. Read more at http://goo.gl/PhgEfq. (Photograph courtesy University of California Irvine)

Burned but not forgotten

"After a fire, things happen that we didn't necessarily think about."

Anne Nolin
Oregon State University

by Agnieszka Gautier

On August 23, 1996 lightning struck north of Waldo Lake in the Cascade Mountains of Oregon. In five days, the Charlton Fire burned 10,000 acres of forest, killing 95 percent of its trees. Almost twenty years later, the area has barely recovered. Dead, bare trees still stand.

Regrowth is stunted. With a drier West prompting more fires, scientists are looking to the longer-term impacts of charred forests.

Fires release a lot of carbon into the atmosphere, increasing carbon dioxide, a greenhouse gas. On a short time scale this heats up the climate. Also, most scientists connect burned forests with

In this photograph, taken eleven years after the Charlton Fire in Oregon's Willamette National Forest, a majority of snags still stand while gradually new vegetation is recovering. (Courtesy M. Spencer)

decreased carbon absorption, further tipping the carbon cycle balance towards warming. But understanding how certain environments respire or store carbon dioxide—crucial for carbon cycle analysis—can be much more complex. This is just what researcher Thomas O'Halloran learned when he looked at the Charlton Fire.

Disturbing events

How disturbed forest patches affect global climate piqued O'Halloran while doing post-doctoral research at Oregon State University (OSU). "The climate impact of forest disturbances extends beyond the carbon budget," said O'Halloran. "To be able to understand and predict carbon in the atmosphere, Earth system models need to include insect outbreaks, wildfire, and hurricanes."

Kelly Gleason, another postdoctoral student at OSU, also looked at the post-fire environment, only from a different angle. O'Halloran analyzed forests before and after disturbances, while Gleason and her team focused on the snowpack in high elevation, burned forests. "No one had studied the effect on snowpack and hydrology," Gleason said. "It's the same process with an interesting paradox." Together, the two studies came together to shed light on the complex relationship between ecosystems and climate.

Life on Earth has synchronized into a symbiotic exchange of oxygen and carbon dioxide. Plants absorb carbon dioxide to make sugars, releasing oxygen; animals eat the sugars, releasing carbon dioxide. Carbon dioxide is only a tiny fraction of the atmosphere, about 0.04 percent, but carbon dioxide and other greenhouse gases trap heat on Earth. Wildfires, burned fossil fuels, and damaged ecosystems all help accrue this heat in

Burned woody debris falls off a charred tree. The area around the tree, with a darkened surface, is melting faster than surrounding snow, which appears lighter. (Courtesy K. Gleason)

the atmosphere, warming the climate and changing our ecosystems.

O'Halloran wanted to measure how disturbances change the way ecosystems exchange carbon dioxide and reflect solar radiation. He utilized the Department of Energy AmeriFlux program, a network of tower sites geared to measure these transfers, but the towers did not sample many insect outbreaks. So O'Halloran looked into the Moderate Resolution Imaging Spectroradiometer (MODIS), a sensor on the NASA Terra and Aqua satellites that can see Earth's entire surface.

Using a subsetting tool from the Oak Ridge National Laboratory Distributed Active Archive Center, O'Halloran could retrieve the exact MODIS pixel that corresponded to the AmeriFlux tower site, and then extrapolate beyond that. In other words, satellite and tower observations could be combined to get more value from the data. "I could poke around and find these disturbances, and easily zoom in and grab MODIS data," said O'Halloran. "And that's where all this started." Now he could compare rates of carbon exchange with albedo and reflected radiation.

Winter reflections

In the Waldo Lake area, the 300-year-old mountain hemlocks measure 20 to 40 meters (65 to 130 feet) tall, and 2 to 3 meters (7 to 10 feet) in diameter. Bark furrows in broad, grey contours. Its needle-like leaves litter the understory. Little light penetrates their continuous canopy, draped in stringy lichen. When fire struck, it vaporized the crowns, leaves, and most branches.

These bare, scorched trunks fracture the landscape. Inside the bark and close to its surface is the foundation of tree life, cambium, a living tissue responsible for growth. If enough heat from a fire kills the cambium, the tree dies. The trunk may stand for decades, but its life has essentially been squelched. From the perspective of solar reflection, these snags, or standing dead trees, behave like living trees. The black of charred bark absorbs sunlight, just as the foliage once did, except it no longer ingests carbon dioxide.

Summer is a time of rejuvenation. "In the summer, vegetation starts to come back, little flowers and herbs initially, and then shrubs and baby trees. As things grow back, the albedo starts to increase again," O'Halloran said. When life re-enters these dead patches, green appears. Green, being lighter than black, reflects more light and increases albedo.

"We knew that for summer and even spring, albedo went up; that had been shown," O'Halloran said. And yet something unexpected was happening in winter. In high-elevation forests, the albedo continued to increase for ten years or more after a wildfire—in winter. "This hadn't been seen before; no one had a good explanation for it," he said.

Into the woods

Disturbed forests modify the carbon and radiation budget for several decades. But how can scientists predict their effect on the climate in the long-term? "This data set extends fifteen years, and the albedo is still high," O'Halloran said. "That's a pretty big climate signal."

While looking at the Charlton Fire, O'Halloran realized that a team of ecologists had long been measuring trees in the Willamette National Forest in Oregon. So O'Halloran could add fifteen years of post-fire field observations to the satellite and tower data, offering the opportunity to investigate the winter increase in albedo.

Steve Acker, an ecologist for the National Forest, joined O'Halloran's study. "It's rare in vegetation ecology to have direct observations," Acker said. Where the fire blazed, the forest elevation rises to 1,700 meters (5,600 feet). "These higher elevation forests haven't received much study," Acker said. "We were able to fill a gap."

Acker observed that over time the burned forest changed. The density of snags decreased. Smaller snags fell first, leaving many of the larger snags to shadow a modest, slow regrowth. O'Halloran said, "The environment is harsh after a fire. It's so cold in the winter. There's no protection. Trees recover slowly."

With just snags standing, sunlight easily penetrates to the surface. In a high-elevation forest, like the Willamette National Forest, snow shrouds the ground from mid-November to about mid-June, as deep as six to seven feet. Only snags stick out of the snowpack. Fallen trees sink beneath. As trees begin to fall, there is less and less dark surface absorbing sunlight.
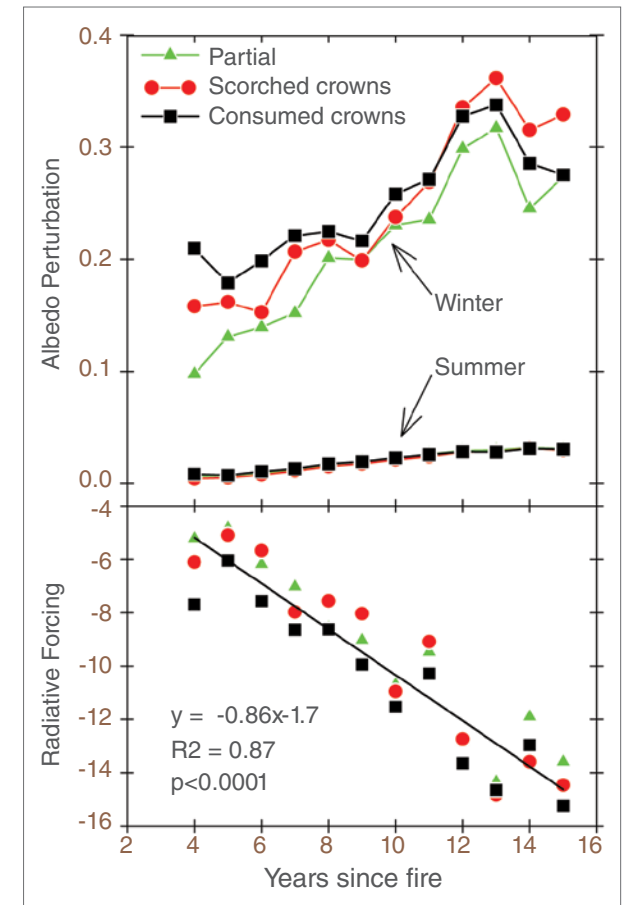
The plot at top shows a time series of the Moderate Resolution Imaging Spectroradiometer (MODIS) albedo, or solar reflection. The effect of fire greatly increases albedo in winter, but only subtly in summer. Three fire classes are presented: partial burn; high severity, scorched crowns; high severity, consumed crowns. The bottom plot of radiative forcing, in watts per square meter, shows that the effect increases linearly with time and is still increasing fifteen years after the fire. (Courtesy T. O'Halloran)

"That's going to keep happening until all the snags fall," O'Halloran said. Eventually, saplings will be taller than the snowpack, and then solar reflection will decrease as new trees take up more light.

A slow fall

Anne Nolin, a professor at OSU and co-author on Gleason's study, said, "After a fire, things happen that we didn't necessarily think about." Gleason's study also used MODIS, but focused on snow cover. "If you burn down a forest, albedo increases hugely," Nolin said. "The albedo of vegetation might be around 40 percent; the albedo of snow is about 80 percent."

Initially fire sends plumes of carbon into the atmosphere, warming it. Over time as snags fall, the landscape gets bleaker. "With a treeless surface, the albedo increases, and more albedo means more sunlight is being reflected, and that's a cooling affect," O'Halloran said. So albedo can offset the warming from carbon dioxide. "They're sort of canceling each other out," he added.

For Gleason, also looking at snow, something else developed. Three years post-fire, during snowfall, she found little difference in snow surface albedo between burned and nearby, unburned forests. "Once snow stopped falling and started melting, the debris that sloughed off charred snags concentrated on the snow surface, darkening it and lowering its albedo," Gleason said. The predominant source of energy for snowmelt is sunlight. With a darker surface and no canopy to block sunlight, the snowpack absorbed 200 percent more sunlight. As a result, snow melted three weeks earlier in the burned forest.

"It's an interesting paradox," Nolin said. On the one hand, snow albedo cools the atmosphere, but the charred debris absorbs more heat, melting snow sooner and faster. "Studies have shown that an earlier snowmelt drives more forest fire disturbance," Gleason said. "The West gets its precipitation in the winter, stored as snow. Snow-

Pileated woodpeckers excavate nests within snags, bringing life to charred forests in Oregon. (Courtesy S. Russell)

This close-up of a dead tree shows depressions and pockets that are key areas for animals to excavate cavities. Pileated woodpeckers, raccoons, and squirrels shelter within. The photo was taken in a subalpine burn on the upper slopes of Mount Harvey, British Columbia at an elevation of 1,600 meters (5,000 feet). (Courtesy D. Brayshaw)

This close-up of charred bark unveils the tree's delicate living tissue. Cambium (orange areas) is the foundation of tree life and growth, giving a tree its rings. If enough heat from a fire kills the cambium, the tree dies. The dead tree may stand for decades. (Courtesy C. J. Reed)

melt provides a moisture subsidy. If snow melts earlier, there is a longer period of drought stress." Gleason hopes her research will help hydrological forecasters, the people on the ground trained to predict how much water is coming out of the mountains and when.

Still, fires are natural. "Fires are ecosystem machines," Gleason said. "They maintain healthy ecosystems." Post-fire environments create heterogeneity in the landscape. Instead of a monoculture of clogged fuels, they increase diversity in forest densities, form microclimates, and open the land to new species. "It's just now we have bigger fires, more intense, higher burn severity, a longer fire season, and more fires," Nolin said. "It's not necessarily bad. It's just that we're still learning what this means."

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References

Gleason, K. E., A. W. Nolin, and T. R. Roth. 2013. Charred forests increase snowmelt: Effects of burned woody debris and incoming solar radiation on snow ablation. *Geophysical Research Letters* 40: 4,654–4,661, doi:10.1002/grl.50896.

Hall, D. K., V. V. Salomonson, and G. A. Riggs. 2006. MODIS/Terra Snow Cover 8-Day L3 Global 500m Grid. Version 5. MOD10A2. Boulder, CO, USA: NASA National Snow and Ice Data Center Distributed Active Archive Center. http://dx.doi.org/10.5067/C574UGKQQU1T.

NASA Land Processes Distributed Active Archive Center (LP DAAC). MODIS/Vegetation Continuous Fields Yearly L3 Global 250m (MOD44B). USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD, 2001, doi:10.5067/MODIS/MOD44B.006.

Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC). 2014. MODIS Albedo (MCD43A). Oak Ridge, TN, U.S.A. https://daac.ornl.gov/MODIS/MODIS-menu/MCD43.html.

O'Halloran, T. L., S. A. Acker, V. M. Joerger, J. Kertis, and B. E. Law. 2014. Postfire influences of snag attrition on albedo and radiative forcing. *Geophysical Research Letters* 41: 9,135–9,142, doi:10.1002/2014GL062024.

For more information

NASA Land Processes Distributed Active Archive Center (LP DAAC)
http://lpdaac.usgs.gov

NASA National Snow and Ice Data Center DAAC (NSIDC DAAC)
http://nsidc.org

NASA Oak Ridge National Laboratory DAAC (ORNL DAAC)
http://daac.ornl.gov

NASA Moderate Resolution Imaging Spectroradiometer (MODIS)
http://modis.gsfc.nasa.gov

About the remote sensing data

Satellites	Terra	Terra	Terra and Aqua
Sensors	Moderate Resolution Imaging Spectroradiometer (MODIS)	MODIS	MODIS
Data sets	Vegetation Continuous Fields Yearly L3 Global 250m (MOD44B)	Terra Snow Cover 8-Day L3 Global 500m Grid, Version 5 (MOD10A2)	Albedo (MCD43A)
Resolution	250 meters	500 meters	500 meters
Parameters	Vegetation	Snow cover	Blue-sky albedo
DAACs	NASA Land Processes Distributed Active Archive Center (LP DAAC)	NASA National Snow and Ice Data Center DAAC (NSIDC DAAC)	NASA Oak Ridge National Laboratory DAAC (ORNL DAAC)

About the scientists

Steven Acker is a zone ecologist with the Northwest Oregon Ecology Group, stationed at the Willamette National Forest. His research interests include effects of fire and fluvial disturbance on vegetation; tree mortality and dead wood accumulation and attrition; and long-term monitoring. The National Science Foundation, the Pacific Northwest Research Station of the U.S. Forest Service, and the Willamette National Forest supported his research. (Photograph courtesy L. Bishop)

Kelly Gleason is a postdoctoral student at Oregon State University. Her research focuses on the interactions of ecosystem disturbance and mountain hydroclimatology, and their implications to snow-water resources in the changing climate system. The National Science Foundation supported her research. (Photograph courtesy K. Gleason)

Anne Nolin is a professor in the College of Earth, Ocean, and Atmospheric Sciences at Oregon State University where she leads the Mountain Hydroclimatology Research Group. Her research focuses on the interactions of climate with mountain snowpacks and glaciers. NASA, the National Science Foundation, and U.S. Geological Survey supported her research. (Photograph courtesy A. Nolin)

Tom O'Halloran is a research assistant professor at Virginia Polytechnic Institute and State University. His research focuses on the role of vegetation, and particularly forests, in regulating Earth's climate. The Department of Energy supported his research. (Photograph courtesy T. O'Halloran)

Stormy vineyards

"To have a direct application that people will use is exciting and it's why we do this type of research."

Kristen Rasmussen
National Center for Atmospheric Research

by Karla LeFevre

Eleven-year old Kristen Rasmussen and her classmates watched from under their desks as a tornado churned past their classroom window. She marveled at the terrifying beauty of the tornado as it whirled over her school playground in Boulder, Colorado. Today, Rasmussen studies intense storm systems all over the globe, tracking weather as unpredictable and intense as the twister she saw as a kid.

Rasmussen, now a postdoctoral research scientist at the National Center for Atmospheric Research, has her sights on storms in subtropical South America, most of which is in Argentina. The storms there are "untamed, intense, and vigorous," much like Argentine wine.

Though wine buffs might recognize that tagline for Malbec World Day, a celebration of Argentina's flagship wine, scientists have discovered that storms from the region bear the same characteris-

Ripe malbec grapes hang from the vine in Mendoza Province, Argentina. (Courtesy I. Lumb)

tics. It turns out Argentina has the perfect terroir that gives both its grapes and storms their distinctive character. But unlike Argentine grapes, little is known about their storms.

With satellite rainfall data and a little creative detective work, Rasmussen and her colleagues are tracking these mysterious storm systems, years after they have dissipated, to ultimately discover how they formed. What they learn could be a boon to science, and to the economies that depend on the fruit of the vine.

Location, location, location

Subtropical South America brews massive storm clusters, called mesoscale convective systems, that are 60 percent larger than those in the United States. They are collections of thunderstorms that reach across the horizon for hundreds of miles and can persist for more than twelve hours. The floods, tornadoes, and hail they unleash can decimate crops. "It's an economic security problem for Argentina," Rasmussen said. "I've seen reports of wineries losing one hundred percent of their crops for a year because of one hail storm."

One area that gets a lot of hail is Mendoza. A province in the foothills of central-west Argentina, Mendoza is home to most of Argentina's vineyards, and produces most of South America's wine. Cabernet sauvignon, chardonnay, and malbec grapes thrive in this high-altitude desert region.

Like other regions in the Andes foothills, Mendoza's geography plays a big role in breeding intense systems that can dump much of a region's annual precipitation all at once, sometimes in the form of grapefruit-sized hail. The Andes funnel warm, moist air from the Amazon down into

Argentina's subtropical arid environment. This provides the convection—rapidly rising warm air mixed with moisture—that fuels severe weather. Rasmussen and her colleagues are among the first to document the mesoscale convective systems in South America. They needed to find out exactly where these systems are happening, and when.

Like an MRI from space

The team became intrigued when radar imagery from the Tropical Rainfall Measuring Mission (TRMM) satellite revealed that this part of Earth is home to both the most frequent large hail in the world and the deepest convective storms. "This region is really special," Rasmussen said. "And because of NASA measurements, we've been able to identify it."

Manuel Zuluaga, a research scientist at the Universidad Nacional de Colombia, said, "We wanted to try to know why, but the first step on the list was to locate the storms." To pinpoint locations, the researchers meticulously tracked the systems, snapshot by snapshot, using sixteen years of TRMM data from the Goddard Earth Sciences Distributed Active Archive Center (DAAC). Electromagnetic echoes that had bounced between the radar instrument and the rain and ice droplets gave shape to the storms. Rasmussen said, "It's like an MRI. It scans the internal pieces and gives us crucial information for understanding the character of the storms." The process helped identify three major types of severe storms within a mesoscale system.

These three types, called deep core, wide core, and broad stratiform, coincide with the phases of a system. Zuluaga explained, "Imagine a big storm with a lot of lightning and wind. The air starts rising, making big, deep plumes that go
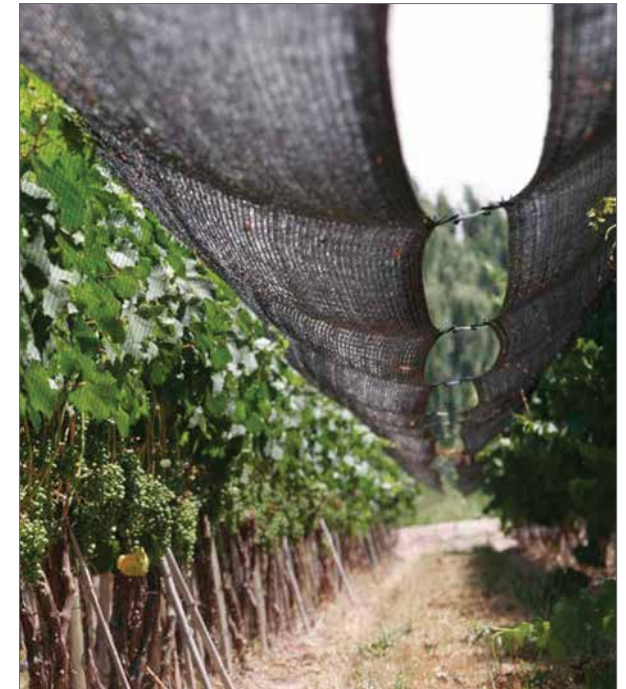
In addition to protection from hail, black nets like this one at the Dominio del Plata winery in Mendoza absorb more of the sun's heat than a white net, which can help the grapes ripen. (Courtesy Vine Connections/Dominio del Plata Winery)

up in the atmosphere. That's what we call deep core. Next, the cells become bigger and shallower, and they become wide cores. Later, when everything is dying out, they become broad stratiform, where the rainfall is light, but widespread." Severe weather follows, cycling from hail near foothills in places like Mendoza to flooding and tornadoes on the La Plata Basin, Argentina's central plains.

Taking things a step further, they looked at average monthly lightning rates. Lightning strikes near severe storms, so information on its whereabouts could corroborate what the radar data showed. Merged data from the TRMM
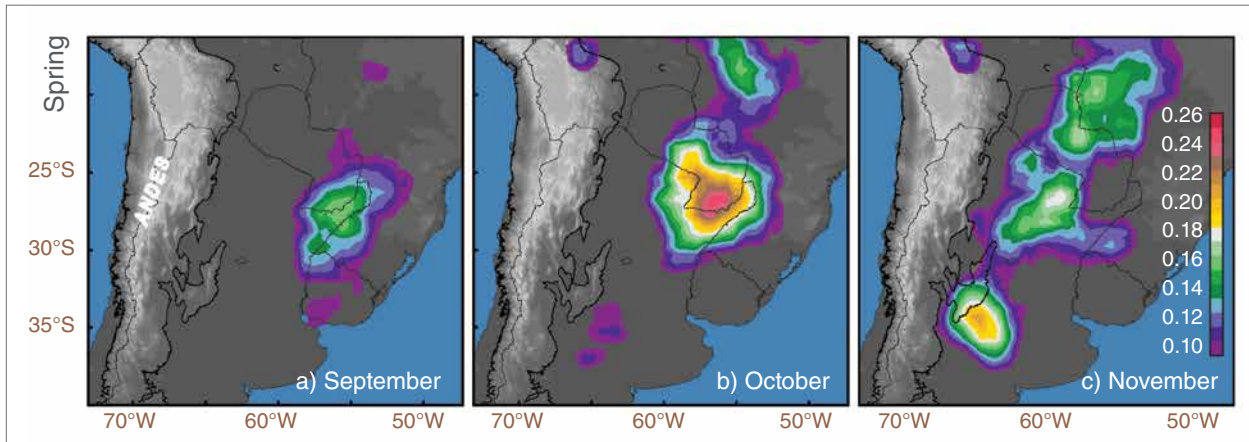
These maps show the average monthly rate of lightning flashes per square kilometer per year in springtime from 1998 to 2013. Red and pink indicate the highest average rate of monthly flashes; purple and magenta the lowest. Thick black lines mark the 0.5 kilometer topography contour on the Andean foothills, where convection initiates severe storms. Data are from the Tropical Rainfall Measuring Mission (TRMM) Lightning Imaging Sensor (LIS) from September through November in subtropical South America. (Courtesy K. L. Rasmussen)

Lightning Imaging Sensor (LIS) and the Optical Transient Detector on Microlab-1, archived at the Global Hydrology Resource Center (GHRC) DAAC, confirmed the locations of the storms. Rasmussen said, "We identified Mendoza as having large amounts of severe episodes of hail. There's also this strong lightning bull's eye right over it."

Ground reporting

With the search narrowed, Rasmussen devised a way to close in further. They needed a map that validated where the three types of storms struck land. This is typically created using in situ measurements, such as meteorological ground stations. But South America has few of these. She realized local newspapers could show major storm events.

Scouring newspaper databases for articles on hail, flooding, and tornadoes, the team gathered the top 100 cases that matched the three storm types

near the time the TRMM satellite passed overhead. Roads and landmarks mentioned in the articles helped them locate the storms on a map.

With the lightning record and a map of storm reports, they created the first detailed profile of the storm conditions in the area. "Now that we have a map of where they happen, we can relate that to what we know about the physics of the atmosphere to learn the causes," Zuluaga said. This helps them improve forecasting models, which will help predict dangerous weather. In an interview with Rasmussen, a spokesperson from the Bodega Norton winery in Mendoza said that installing nets to protect against hail is very expensive, almost $10,000 per hectare, so some producers cannot afford them. The government uses a program of cloud seeding to destroy the hail, but it is done only east of Mendoza. Better forecasting of the storms that hit all regions could help the Argentine government target them more effectively in the future.

How a storm grows

In the meantime, improvements in satellite instruments will help Rasmussen and her colleagues collect more nuanced information. TRMM was decommissioned in June 2015, but the Global Precipitation Measurement (GPM) satellite is now orbiting Earth in its place. Zuluaga said that GPM's ability to sense dual wavelengths allows them to study mid-latitudes and see more ice in clouds than before.

Another crucial piece for the team is ground measurements. "We need to profile the atmosphere to understand more about how these systems form," Rasmussen said. "A satellite-based radar gives us snapshots, so we only capture certain times in their life cycle. What we'd really like to do is observe these systems from beginning to end and understand how they grow."

A ground-based radar called S-Band Dual-Polarization Doppler Radar (S-Pol) that can scan the atmosphere continuously will help them do just that. The team is busy planning a field campaign with the Argentinian Meteorological Service and researchers at the University of Buenos Aires to begin using S-Pol.

Along with instruments on the ground, humans are helpful, too. In the United States, storm spotters trained by the National Weather Service and other agencies regularly report hail sizes or tornadoes. It will take time to train citizen scientists in Argentina, and to develop a national system for archiving their observations.

Yet Rasmussen is optimistic. "There are a lot of people that live in this region," she said. "They don't yet have the capability to look at these storms with their own networks, but we are able

to provide information that could help save human life and property. We could warn vintners they might have a flood, or notify people when there's a severe storm on its way. To have a direct application that people will use is exciting and it's why we do this type of research."

To access this article online, please visit https://earthdata.nasa.gov/sensing-our-planet/stormy-vineyards.

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References

Cecil, D. J., D. Buechler, and R. Blakeslee. 2014. LIS/OTD 0.5 Degree High Resolution Monthly Climatology (HRMC) Data. Available online from the NASA EOSDIS Global Hydrology Resource Center Distributed Active Archive Center (GHRC DAAC). Huntsville, AL, USA. doi:10.5067/LIS/LIS-OTD/DATA303.

Christian, H., S. Goodman, and R. Blakeslee. 2014. NASA Marshall Space Flight Center (MSFC) Lightning Imaging Sensor (LIS) Science Data. Available online from the NASA EOSDIS Global Hydrology Resource Center Distributed Active Archive Center (GHRC DAAC). Huntsville, AL, USA. doi:10.5067/LIS/LIS/DATA201.

Houze, R. A., Jr. 2004. Mesoscale convective systems. *Reviews of Geophysics* 42, doi:10.1029/2004RG000150.

NASA Goddard Earth Sciences DAAC (GES DAAC). 2014. TRMM 2A-23 and 2A-25 products. Greenbelt, MD, USA. http://disc.sci.gsfc.nasa.gov/daac-bin/DataHoldingsPDISC.pl.

Rasmussen, K. L., M. D. Zuluaga, and R. A. Houze Jr. 2014. Severe convection and lightning in subtropical South America. *Geophysical Research Letters* 41: 7,359–7,366, doi:10.1002/2014GL061767.

For more information

NASA Global Hydrology Resource Center Distributed Active Archive Center (GHRC DAAC)
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NASA Goddard Earth Sciences DAAC (GES DAAC)
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About the remote sensing data

Satellites	Tropical Rainfall Measuring Mission (TRMM)	TRMM
Sensors	TRMM Precipitation Radar (PR) TRMM Lightning Imaging Sensor (LIS)	Optical Transient Detector (OTD)
Data sets	TRMM PR V7 2A25 data	LIS/OTD HRMC from TRMM LIS and Microlab-1 OTD TRMM LIS Orbital Science Data
Resolution	4-5 kilometer horizontal, 250 meter vertical resolution at nadir	0.5 degree
Parameters	Radar reflectivity and rain type	Lightning rates Lightning flashes and sensor viewing time Raw flash count
DAACs	NASA Goddard Earth Sciences Distributed Active Archive Center (GES DAAC)	NASA Global Hydrology Resource Center DAAC (GHRC DAAC)

About the scientists

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